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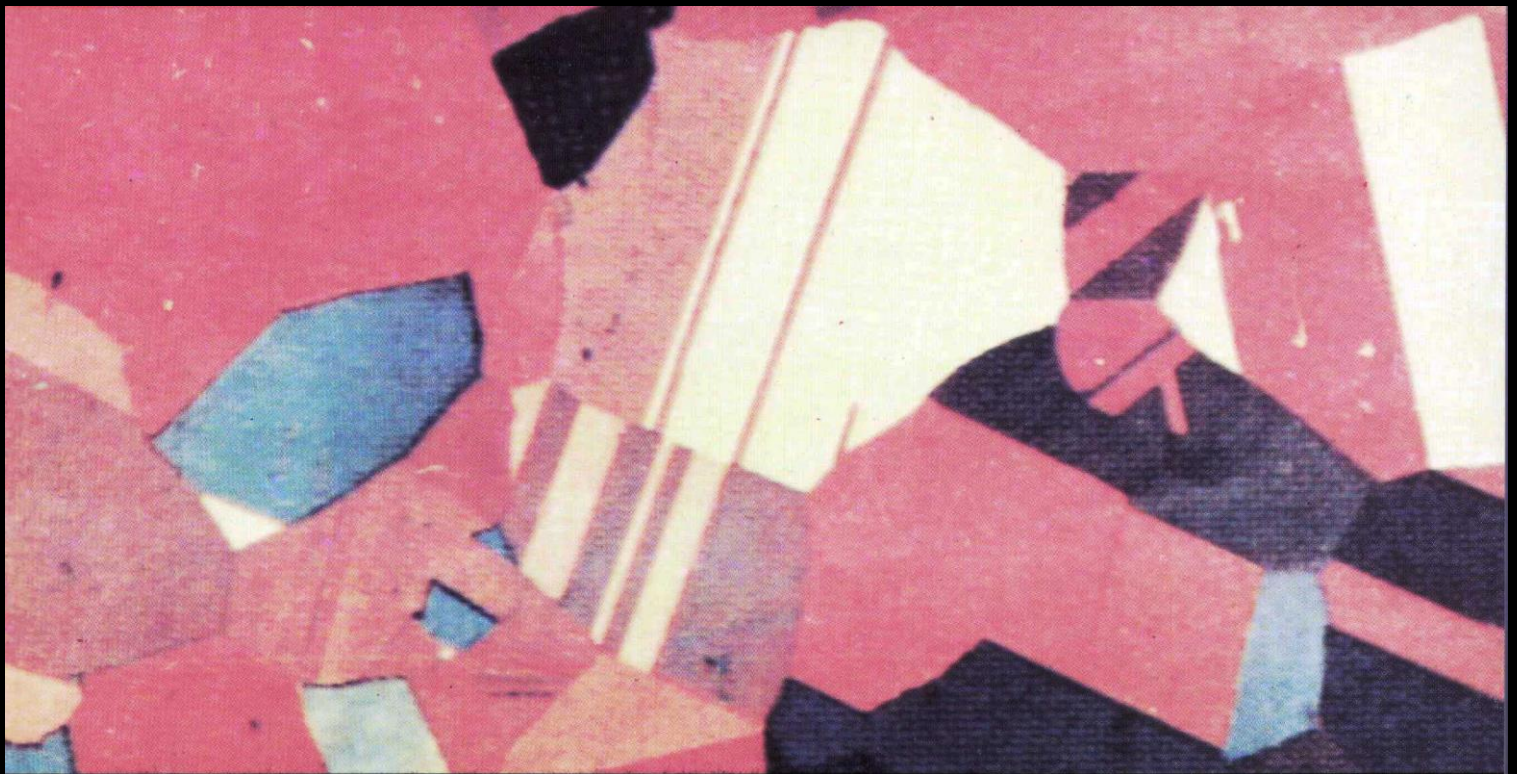
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Section A: MINING

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Grozdanka D. Bogdanović



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Republic of Serbia.***

Introduction to the 60th Issue of the Journal of Mining and Metallurgy: Section A Mining

University of Belgrade, Technical Faculty in Bor has been publishing the Journal of Mining and Metallurgy since 1965, which was recognized as a journal of national importance in the former Yugoslavia. In 1997, it was split into two independent journals dealing separately with mining and metallurgy.

In 2024, the 60th volume of the Journal of Mining and Metallurgy – Section A: Mining was published, marking 27 years of continuous and uninterrupted publication. During this time, the journal has become a leading national publication of international importance, according to the categorization of domestic scientific journals in the fields of energy, mining and energy efficiency.

Journal of Mining and Metallurgy A: Mining is an Open Access (OA) journal. The high visibility of the articles published in Journal of Mining and Metallurgy A: Mining is permanently guaranteed by SCIndeks and further improved by the automatic re-

indexing of the metadata in DOAJ and the article full text in Google Scholar.

The number of online accesses, downloads and citations has reached a satisfactory level and continues to rise. We hope that the journal will continue on its path of development and become the highest ranking journal in the global scientific databases.

As we look back on the years of continuous publication of the journal, we would like to thank all the dedicated editors, editorial boards, researchers and reviewers who have initiated, shaped and promoted the development of the journal. Their commitment and expertise have contributed significantly to the high quality of the online and printed editions of the journal.

On behalf of the editorial team, we wish all our authors and reviewers, readers and colleagues, an extremely productive and joyful New Year 2025.

Editor-in-Chief

NEW EDITORIAL BOARD MEMBER



Lijie Guo

PERSONAL DETAILS

Born: May 24, 1980

Occupation: Professor

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CAREER OBJECTIVE

Rock Mechanics, Mining with backfill, Tailings management, Slag utilization.

EDUCATION

B.Sc. in Mining Engineering, Jiangxi University of Science and Technology(JUST), Ganzhou, CHINA, 2004.

M.Sc. in Mining Engineering, Beijing General Research Institute of Mining and Metallurgy, Beijing, CHINA, 2007.

D.Sc. in Mining Engineering, Central South University (CSU), Changsha, CHINA, 2016.

Ph.D. DISSERTATION

Title: Research on Material Features and Mechanical Characteristics of Cemented Rock-Tailings Backfilling

Supervisor: Keping Zhou

PROFESSIONAL EXPERIENCE

2016–2018, Professor, Beijing General Research Institute of Mining and Metallurgy, China.

2018–2019, Visiting Professor, University of Toronto, Toronto, Canada.

2019–in progress, Professor, Beijing General Research Institute of Mining and Metallurgy, China.

PROFESSIONAL AFFILIATIONS AND MEMBERSHIPS

1. Member, Canadian Institute of Mining, Metallurgy and Petroleum (2007 - 2024).

2. Member, Chinese Society for Rock Mechanics and Engineering (2012 - 2024).

3. Member of International MineFill Council (2019 - 2024).

OTHER SKILLS AND QUALIFICATIONS

1. Research on Material Features and Mechanical Characteristics of Cemented Rock-Tailings Backfilling, National Natural Science Foundation of China, 2011.01-2013.12, Chief Investigator.

2. Research on filling materials and optimization technique in the process of deep mining, The National Key Technology Research and Development Program, Ministry of Science and Technology of China, 2013.01-2016.12, Chief Investigator.

3. Research on Cemented Paste Backfill Technology of Deep Mine, International Science & Technology Cooperation Program of China, Ministry of Science and Technology of China, 2014.04-2017.04, 2nd-Chief Investigator.

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- A3.** Zhang, Y., Zhang, Z., Du, X., Guo, L., Liu, G. (2023). A 2D roughness method for irregular interface of rock-backfill. *Construction and Building Materials*, 397, 132380.
- A4.** Ma, Q., Liu, G., Yang, X., Guo, L. (2023). Physical model investigation on effects of drainage condition and cement addition on consolidation behavior of tailings slurry within backfilled stopes. *International Journal of Minerals, Metallurgy and Materials*, 30(8), 1490-1501.
- A5.** Zhang, L., Guo, L., Zhao, Y., Li, M. (2022). Properties of Unburned Brick Produced by Entirely Waste-Stream Binder Activated by Desulfurization Gypsum. *Metals*, 12(12), 2130.
- A6.** Tian, G., Zhang, Z., Guo, L. (2022). Hydro-Mechanical-Chemical Coupled Model for Solute Transport Considering the Influence of Entrapped Bubbles. *Environmental Engineering Science*, 39(4), 320-328.
- A7.** Guo, L., Peng, X., Zhao, Y., et al. (2022). Experimental study on direct tensile properties of cemented paste backfill. *Frontiers in Materials*, 9, 864264.
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- A9.** Zhang, Y., Zhang, Z., Guo, L., et al. (2021). Strength Model of Backfill-Rock Irregular Interface Based on Fractal Theory. *Frontiers in Materials*, 8, 792014.
- A10.** Guo, L., Li, W., Namdar, (2021). A. Using recycled aggregate for seismically monitoring of embankment-subsoil model. *Case Studies in Construction Materials*, 15, e00605.

NEW EDITORIAL BOARD MEMBER



André Carlos Silva

PERSONAL DETAILS

Born: 30/06/1978, Itabirito, MG, Brazil

Occupation: Associate professor

Address: Rua Eurípedes Pereira Ferreira, 431, Margon III, Catalão/GO, CEP 75.713-065, Brazil

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CAREER OBJECTIVE

Was a CNPq researcher at DT-2 and PQ-2 level. Associate Professor III at the Faculty of Engineering (FENG) at the Federal University of Catalão (UFCAT). He was coordinator of the Postgraduate Program in Exact and Technological Sciences (PPGCET), from 01/2020 to 01/2024. Has experience in Mining and Materials Engineering, with emphasis on mineral processing.

EDUCATION

B.Sc. in Mining Engineering, Federal University of Ouro Preto, 2000.

M.Sc. in Mineral Engineering, Federal University of Ouro Preto, 2003.

D.Sc. in Materials Engineering Federal University of Ouro Preto, 2010.

Post-doc, Federal University of Minas Gerais, 2015).

Post-doc, Technische Universität Clausthal, 2018.

Ph.D. DISSERTATION

Title: Computer simulation of direct reduction of iron ore in MIDREX furnaces

Supervisor: Américo Tristão Bernardes

PROFESSIONAL EXPERIENCE

2001 – 2004, Lecturer, Centro de Ensino Tecnológico de Itabirito Cefet MG

2003 – 2005, Lecturer, Universidade Federal de Ouro Preto.

2005 – 2008, Lecturer, Faculdade Santa Rita.

2008 – 2010, Lecturer, Centro Universitário Presidente Antônio Carlos, UNIPAC, Brasil.

2010 – Present, Associate Professor, Federal University of Catalão.

PROFESSIONAL AFFILIATIONS AND MEMBERSHIPS

Associated editor of the Technology in Metallurgy, Materials and Mining journal (TMMM) and reviewer of the journals: International Journal of

Mining, Materials, and Metallurgical Engineering, Mineral Processing and Extractive Metallurgy Review, Minerals, Journal of Materials Research and Technology, Powder Technology, International Journal of Mineral Processing, Journal of Dispersion Science and Technology, Carbohydrate Polymers, Tunnelling and Underground Space Technology, American Association for Science and Technology, Anais da Academia Brasileira de Ciências, Revista Escola de Minas, Holos and Tecnologia em Metalurgia, Materiais e Mineração.

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- A2.** Silva, L.A., Silva, A.C., SILVA, E.M.S. (2024). Flotation tests using sorghum flour as a pyrochlore depressant. *REM - International Engineering Journal*, 77, 75 - 82.
- A3.** Nogueira, F., Rodrigues, K., Pereira, C., Silva, A.C., Silva, E.M.S., Azizi, A., Hassanzadeh, A. (2023). Quartz Fine Particle Processing: Hydrophobic Aggregation by Shear Flocculation. *Minerals*, 13, 1208-12.
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- A6.** Mata, C.E.D., Pereira, C.A. Silva, A.C., Sousa, P.L.R. (2020). Characterization of the Angico dos Dias alkaline-carbonatite complex for phosphate rock processing. *Journal of Materials Research and Technology*, 9, 12236-12243.
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- A9.** Silva, A.C., Cara, D.V.C., Silva, E. M. S., Leal, G. S., Machado, A. M., Silva, L. M. (2018). Apatite flotation using saponified baker's yeast cells (*Saccharomyces cerevisiae*) as a bioreagent. *Journal of Materials Research and Technology*, 8, 752-758.
- A10.** Silva, A. C., Carolina, S. D., Sousa, D. N., Silva, E. M. S. (2018). Feldspar production from dimension stone tailings for application in the ceramic industry. *Journal of Materials Research and Technology*, 8, 1-7.
- A11.** Silva, E. M. S., Peres, A. E. C., Silva, A. C., Leal, M. C. M., Lião, L. M., Almeida, V. O. (2018). Sorghum starch as depressant in mineral flotation: part 1 - extraction and characterization. *Journal of Materials Research and Technology*, 1, 1-7.
- A12.** Silva, E. M. S., Peres, A. E. C., Silva, A. C., Florêncio, D. L., Caixeta, V. H. (2018). Sorghum starch as depressant in mineral flotation: part 2 - flotation tests. *Journal of Materials Research and Technology*, 1, 1-8.

NEW EDITORIAL BOARD MEMBER



Maria Sinche-Gonzalez

PERSONAL DETAILS

Born: Peru

Occupation: Assoc. Professor

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CAREER OBJECTIVE

My goal is to build a strong career in research and teaching and currently is the main supervisor of four (4) PhD doctoral researchers and the consortium coordinator of the Erasmus Mundus Master PROMISE. I have worked twelve years in the mining industry gaining expertise in the flotation of polymetallic sulphide minerals working as a senior metallurgist in various mining companies.

My experience in research and teaching is seventeen years working in Ian Wark Institute, Luleå University of Technology and the University of Oulu.

I have an in-depth knowledge on the design and optimisation of flotation circuits as well as geometallurgy and experience with modelling and simulation software for mineral processing and flowsheet development.

In my PhD research I specialise in flotation and surface chemistry. I have carried out extensive flotation and comminution circuit surveys working in operation, pilot plant campaigns and metallurgical laboratories in Peru, Australia and internationally.

I have been involved in projects and technical studies related to most key mining commodities – copper, lead, zinc, iron, gold, phosphate.

EDUCATION

Licentiate in Education Sciences, Catholic Santa Maria University, 1992.

B.Sc. in Metallurgical Engineering, San Agustin National University of Arequipa 1994.

Professional Eng. of Metallurgy, San Agustin National University of Arequipa, 1996.

Bachelor in Business Administration, Garcilazo de la Vega University, 2006.

Master in Sustainable Management of the Mineral Resources, Madrid Polytechnic University, 2007.

PhD in Mineral Processing, University of South Australia, 2014

Docentship in Mineral Processing, University of Oulu, 2018.

Ph.D. DISSERTATION

Title: Sinche-Gonzalez, M., The influence of recycled process water quality on the flotation of copper and molybdenum sulphide flotation,

University of South Australia, 2014, URRSA David Murray Collection DM 622.752 GONM, Bibliographic Id 9915866605401831

Supervisor: Daniel Forniero

PROFESSIONAL EXPERIENCE

May 2016 - ongoing: Senior University Lecturer in mineral processing-Adjunct Professor, Oulu Mining School, University of Oulu, Finland, permanent position

01.2015-04.2016 Invited Researcher, Mineral and Metallurgy Department, Luleå Technological University

01.2014-12.2014 Research Engineer, Waten-ST/Geoperaciones Consultancy Company, Peru & Australia

02.2010-12.2013 PhD research, Ian Wark Research Institute – University of South, Australia

10.2007-01.2010 Research assistant in Mineral Processing, Ian Wark Research Institute, UNISA, Australia

In Industry

12.2011-04.2012 Senior Project Metallurgist, Newmont–Yanacocha mine, Peru (Au-Cu Expansion)

08.2013-11.2013 Project Manager, Amira-UNISA, BHP, Prominent Hill (Cu plant)

05.2004-11.2005 Senior Mineral Processing Engineer, Pan American Silver, Huaron Mine (Cu, Pb, Zn mine)

05.2002-05.2004 Process Engineer, Mining Company Ares, Grupo Hochschild–Peru (Ag-Au mine)

08.2000–04.2002 Senior Mineral Processing Engineer, Condestable Mine, Group Trafigura, (Cu treatment)

01.1996-08.1999 Manager Metallurgical Laboratory, Quirulvica Mine, Panamerican Silver SAC, Peru

04.1994-12.1995 Mineral Processing Engineer Concentrator Plant company EMMYN, Potosi, Bolivia

01.1994-03.1994 Traineeship on Mineral

Processing, Porco Mine, Compania Minera del Sur, Bolivia

01.1993-04.1993 Traineeship on Smelter Aceros Arequipa (Arequipa Steels), Ica, Peru

PROFESSIONAL AFFILIATIONS AND MEMBERSHIPS

2016-Present: Member Mining Engineering and Mineral Processing & Geophysics Research Community (MEMPGF-RC), University of Oulu

2015-Present: Associated Member, Engineers Australia

1999-Present: Associated Member, Institute of the Mining Engineers from Peru

1996-Present: Associated Member, Professional College of Engineers of Peru

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Expert registration for the European Commission No. EX2017D299742, (EX2021-D423156)

2014 Registration in the Teacher Registration Board of South Australia

1998-Present Member of the Professional Professors College from Peru.

Reviewer for 7 journals

OTHER SKILLS AND QUALIFICATIONS

Diploma in Geometallurgy, CAMIPER Peruvian Chamber of Mining

Diploma in Project Management, at TAFESA - Technical and Further Education South Australia

High specialization course in Quality and Environment Management, norms ISO 9000 and ISO 14000, 1999, Madrid, Spain, 120 h.

Excellent user of Microsoft suite includes Excel, Word, PowerPoint, MS Project, PHREEQC, SPC, HSC-SIM Chemistry, JKSIM, SPSS.

Knowledge of multiple analyses FA, UV/Vis spectrophotometer, PSD in mastersizer, zeta potential in malven zetasizer and cilas, Loud Speaker contact angle, ICP-EOS, XRD, XRF, SEM, XPS.

LIST OF SELECTED REFERENCES**A1. Peer reviewed paper**

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- [2] Herrera, N., Sinche-Gonzalez, M., Okkonen, J., Mollehuara, R. (2024). Predicting flowability at disposal of spent heap leach by applying Artificial Neural Networks based on operational variables, *Minerals*, 14(1), 40,
- [3] Herrera, N., Sinche-Gonzalez, M., Okkonen, J., Mollehuara, R. (2023). Soft Computing Application in Mining, Mineral Processing and Metallurgy with an Approach to Using It in Mineral Waste Disposal, *Minerals*, 13(11), 1450.
- [4] Käyhkö, T., Sinche-Gonzalez, M., Khizani-shvili, S., Liipo, J. (2022). Validation of predictive flotation models in blended ores for concentrator process design. *Minerals Engineering*, 185, 107685.
- [5] Sinche-Gonzalez, M., Fornasiero, D. (2021). Understanding the effect of sulphate in mining-process water on sulphide flotation. *Minerals Engineering*, 165, 106865.
- [6] Sinche-Gonzalez, M., Fornasiero, D. (2021), Efecto del sulfato en el agua de proceso de minería sobre la flotación de sulfuros. - *Revista Minería*, 523, 18-28.
- [7] Tanhua, A., Sinche-Gonzalez, M., Kalapudas, R., Tanskanen, P., Lamberg, P. (2020). Effect of waste rock dilution on spodumene flotation. *Minerals Engineering*, 150, 106282.
- [8] Heiskari, H., Kurki, P., Luukkanen, S., Gonzalez, M. S., Lehto, H., Liipo, J. (2019). Development of a comminution test method for small ore samples. *Minerals Engineering*, 130, 5-11.
- [9] Kallio, R., Luukkanen, S., Sinche Gonzalez, M., Tanskanen, P., Lamberg, P., Jylänki, J., Liipo, J. (2018). Mineralogical characterization of lithium and Fe-Ti-V ore flotation tailings, *Process Mineralogy* '18.
- [10] Sinche-Gonzalez, M., Fornasiero, D., Zanin, M. (2016). Flotation of Chalcopyrite and Molybdenite in the Presence of Organics in Water. *Minerals*, 6(4), 105.
- [11] Sinche-Gonzalez, M., Lamberg, P., Suup, M. (2016). Geochemical Model and Simulation of Water Balance for Mining Operations: Svappavaara Iron Mine. *Modern Environmental Science and Engineering*, 2, 721-728.
- [12] Sinche Gonzalez, M. (2007). Assessment of the environmental behaviour of the metallurgical and mining solid waste (RSMM) by sequential extraction method and application of mobility and transport models. *Journal of the Research Institute of Geology, Mines, Metallurgy and Geographical Science*, (10), 19, 78-86.

A2. Scientific books

- [1] P. Martinez, M. Sinche Gonzalez, R. Mollehuara-Canales, M. Martinez. Mechanical operations of solid liquid separation: application in beneficiation plant of metallic and no metallic minerals, 2023 ISBN eBook: 9788419786838 (In Spanish).
- [2] Sinche Gonzalez, Maria, Chapter 5 Modelling and simulation of water balance for mining operations. In: Book title *Water Conscious Mining (Wascious)*. Edition: TemaNord, ISSN 0908-6692; 2017:525, Publisher: Nordic Council of Ministers, ISBN: 978-92-893-4961-1.

A REVIEW OF THE STRATIGRAPHIC CHARACTERISTICS AND AGE DATA OF THE MAIN ROCK UNITS IN THE BOR METALLOGENIC ZONE (TIMOK MAGMATIC COMPLEX)

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Received: January 9, 2024; Accepted: April 18, 2024

Abstract

This study reports on the stratigraphic characteristics of the main units and indicates the link between magmatism and mineralization in the Bor Metallogenic Zone (BMZ) - the Timok Magmatic Complex (TMC). Existing data are supplemented by the latest different systematic long-term geological and stratigraphic surveys and new and contemporary mineral exploration methods. The TMC extends on a continental crust composed of different types of the Proterozoic to the Lower Cretaceous units and consists of the volcanic/magmatic, volcanogenic-sedimentary and sedimentary rock packages. Sedimentary processes and magmatism were almost continuous throughout the Late Cretaceous. The sedimentation lasted from the Albian-Cenomanian to the Maastrichtian. Magmatism occurred in at least two phases from the Upper Turonian to the Upper Campanian: I volcanic phase - V1 (90-82 Ma), II volcanic phase - V2 (83-78 Ma), with a steady decrease in age from east to west. Cu-Au porphyry mineralization occurs between 87-80 Ma. The major epithermal and porphyry mineralization is related to the V1 magmatic phase predominantly developed in the easternmost part of the BMZ.

Key words: Bor Metallogenic Zone, Timok Magmatic Complex, stratigraphy, volcanism, age data, mineralization.

1. Introduction

The Timok Magmatic Complex (TMC) overlaps almost completely with the Bor Metallogenic Zone (BMZ), which belongs to the Late Cretaceous Apuseni-Banat-Timok-Srednogorje Belt (ABTS, [1,2]) and together belong to the transcontinental Tethyan-Eurasian Metallogenic Belt [3]. Because the TMC and the BMZ as the entire ABTS are known to host some of the largest Cu and Au deposits in Europe, their geology has been systematically studied over a long period of time (e.g., [4,5,6,7,8,9,10,11] among others). The studies covered various geological aspects of the origin and evolution of many parts of this belt and established solid genetic links between volcanic/magmatic processes and mineralization events. In this respect, the information based on stratigraphic relationships and high precision geochronology that includes Ar/Ar [5,6], U/Pb zircon dating (e.g., [4,9,11,12,13]) and Re/Os molybdenite dating [7] was of paramount importance.

In this study, the stratigraphy, mineralization relationships and radiometric age data of the rocks and mineralization of the BMZ (TMC) are revised,

supplemented and systematized. The term TMC is used in the discussion on stratigraphy and age data and BMZ on mineralization and ore deposits. The existing data are supplemented by the latest different long-term systematic stratigraphic and geological relationships established by field observations and new and contemporary mineral exploration methods (primarily exploration drilling), as well as a series of published radiometric ages for volcanic rocks and mineralization. The BMZ is famous for its more than one hundred significant metallic occurrences 22 of which have been recorded as ore deposits (see review of [17]). Some of them are world class porphyry copper systems with high- intermediate- and low-sulphidation epithermal Cu-Au, or Au ore deposits [14,15,16,17,18]. For a long time, it was believed that the old, long-explored areas were unpromising in terms of discovering new ore bodies, but research over the last 15 years and the discovery of Čukaru Peki, a large copper and gold deposit, are rekindling interests in further investigating of the BMZ, both in research and scientific context [19,20,21,22,23,24].

Systematically collected latest research data

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presented in this paper confirm that the main mineralization phase in the BMZ was formed during the I (first) volcanic phase (V1) which was formed in the easternmost part of the TMC. In addition, the I volcanic phase yielded both mineralized and non-mineralized andesitic subgroups of rocks (V1A and V1B) with subtle but measurable and macroscopically visible petrological differences, which may lead to new insights into the main mineralization event in this area [12,19,23,24]. On the other hand, according to previous researches, there are numerous different morphogenetic types of mineralization in the central and western part of TMC, which is most likely related to the II (second) volcanic and magmatic phase (V2), but is less promising in terms of the discovery of significant deposits of porphyry copper [11,17]. The age of the rocks in TMC and their relationship with the existing mineralization is reviewed and commented on in a separate section of this study.

2. Stratigraphy of the BMZ (TMC)

The geology of the TMC and the location of the major ore deposits are given in Figure 1. The stratigraphy and time space development of the TMC and the relationships between the published sedimentary formations and volcano-sedimentary units, magmatic suites and mineralized rocks [8,25,26,27] are given in Figure 2. The TMC developed on a continental crust composed of different types of the Proterozoic to the Lower Cretaceous rocks partially overlaid by Miocene and Holocene sediments (M in Figure 2). Late Cretaceous units in the TMC that we will focus on in this study are: Sedimentary formations (Lenovac Formation, Oštrej Formation, Bor Clastic and Bukovo Formation); volcanic-sedimentary unit (Metovnica Epiclastite); magmatic suites (Timok Andesite, Osnić Basaltic andesite, Ježevica Andesite, and Valja Strž Plutonite).

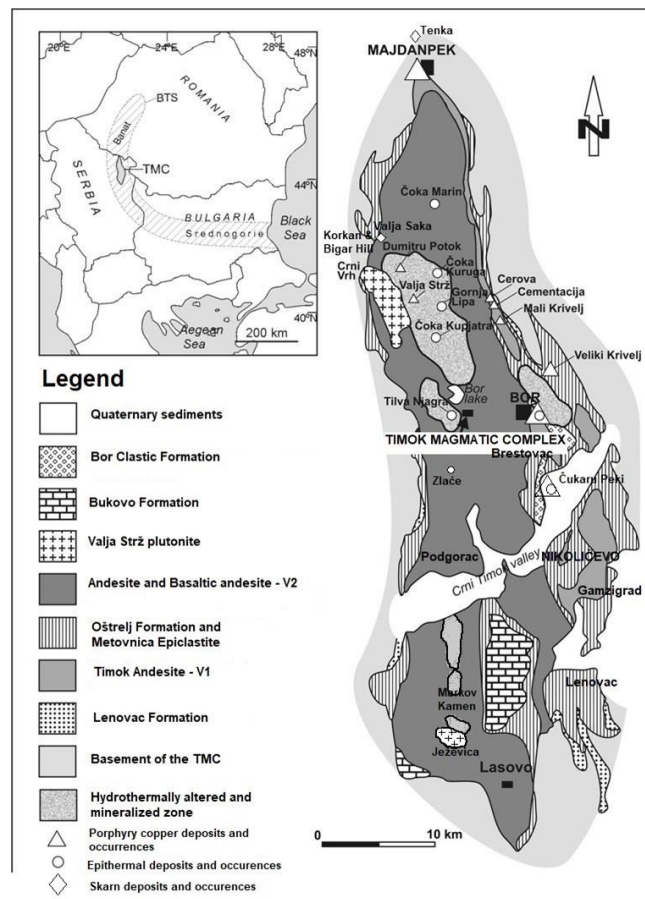


Figure 1 Simplified geological map of the TMC with the locations of major ore deposits and toponyms mentioned in this paper; the inset shows the regional geotectonic position

After a continuous carbonate sedimentation from the Early Jurassic to the Lower Cretaceous (Figures 2, 2a), a new sedimentation period commenced with the Albian transgression and unconformably overlies the Lower Aptian sandy limestones, (Figure 2). These Albian–Cenomanian sedimentation processes had clastic character and were related to oscillations and changes in the sedimentation regime of the depositional environment (Lenovac Formation, [26,27], LE in Figure 2). In the literature, this formation is also referred to as Stublica Clastics [25], but it was first described as Lenovac Beds [28] and therefore the author accepted this name for the Formation. This geological unit is built of sandy claystones, sandy marlstones and sandy siltstones topped by sandstones with siderite, and often rich in planktonic foraminifera content from the Upper Albian–Cenomanian [25].

After a hiatus, the Turonian–Senonian evolution commenced with a new sedimentary cycle. The sediments discordantly overlie the Lenovac Formation (Figure 2b). This started with basal conglomerate and continues over wide area in the TMC with clastic to carbonate sediments (Oštrej Formation, [25], OS in Figure 2). The lowest part of the sediments contains microfauna (usually *Helvetoglobotruncana helvetica*), indicating the Lower to the Middle Turonian age [25]. During the Upper Turonian to the Senonian, the whole TMC area shows a considerable difference in the evolution between the eastward and the westward tectonic block (Timok East and Timok West in Figure 2 [26]).

In the eastward block, predominate volcanic rocks of biotite-hornblende andesite (\pm dacite) compositions (Timok Andesite, [8,12], V1 in Figure 1, 2). These rocks stratigraphically overlie the Lenovac Formation or the Turonian clastic to carbonate sediments (Oštrej Formation, Figure 1). The available U/Pb zircon ages of the V1 andesite phase range 90–82 Ma [4,9,12,13]. The V1 andesite phase can be subdivided into two different andesite sub-phases: V1A (older) and V1B (younger, Figure 2c), which systematically differ in their stratigraphic position and petrography, age, and their link to mineralization [12,23,24].

The V1A sub-phase (older) andesite can be termed plagioclase-hornblende phyric, has predominantly holocrystalline (glass-free) groundmass and with the relative number of phenocrysts higher than 50% vol. In this andesite plagioclase, phenocrysts predominate over hornblende pheno- and microphenocrysts, both in terms of size and relative abundance (Figure 2c). The rock is

represented by coherent lava flows, shallow intrusions (dykes and domes – P1 in Figure 2), monomictic breccia (autobreccia and hyaloclastites) and different facies of monomictic syn-eruptive volcanoclastic rock. The textural characteristics of the V1A volcanites unequivocally indicate the non-explosive (effusive) character of volcanism, and the monomictic composition of the volcanoclastic indicates their volcanogenic origin. The age of the V1A (Table 1) ranges widely from 90 to 85 Ma [4,5,6,7,12]. They are all situated and related to the V1 (V1A) magmatic phase [24]. The V1A andesite is strongly altered and mineralized by epithermal high sulphidation massive Cu–Au ore and/or porphyry disseminations or stockwork ([12,21,22,23,24], Figures 2d,e) and hosted the world-class epithermal, high-sulphidation Cu–Au deposit of Bor and Čukaru Peki–Upper zone and large porphyry Cu–Au deposits of Veliki Krivelj, Majdanpek, Bor-Borska Reka and Čukaru Peki–Lower zone. As mentioned above, the latest researches, primarily [12,13,21,22,23,24] indicate that the rocks of the V1A sub-phase are the hosts of mineralization in the Čukaru Peki deposit. The thickness of the entire V1A package is significantly greater than 1500 m. However, [23] showed that precisely in the Čukaru Peki deposit V1A sub-group was divided into three groups according to the texture (size and amount of phenocrysts) and the degree of mineralization.

The V1B sub-phase (younger) can be termed hornblende-plagioclase phyric andesite. It is a fresh, non-mineralized rock displaying holo- to hypocrySTALLINE texture and occasionally fluidal fabric. The hornblende phenocrysts are clearly noticeable, often large and much more represented than in V1A (Figure 2c). The V1B is represented by coherent, brecciated and volcanoclastic facies formed via submarine effusive eruptions. This unit is in Čukaru Peki deposit up to 200 m thick [23]. The V1B sub-phase shows an age (Table 1) range of ~85 to 83 Ma [4,12]. The V1B is overlain by the Metovnica Epiclastites or gray to reddish marls of the Oštrej Formation (Figure 2).

During the volcanism and especially after its interruption, in a shallow water environment, andesite volcanics begin to be resedimented, transported and formed post-eruptive volcano-sedimentary package – epiclastic. These rocks are known as the Metovnica Epiclastite [8], (ME in Figure 2). The ME are represented by polymictic andesite breccia, volcanoclastic conglomerate and sandstone, with clasts of volcanic and non-volcanic origin. Matrix is often composed of clay, fine grained sandstones or reddish

marls. The clasts are usually semi-rounded to rounded, less often semi-angular (Figure 2f). The composition of the clasts differs in the Timok East block and the Timok West block of the TMC. In the east it is mainly clasts of Timok andesite - V1, while in the west it is mainly clasts of andesite and basaltic andesite - V2. ME are often layered and laminated, usually interlayered with marls and siltstone. ME sometimes contain well-preserved microfauna the Coniacian–Campanian age and in the wider area of the copper deposits contain a significant amount of altered and mineralized clasts ([8,12,26,27,29], Figure 2f).

The sedimentary series of the Oštrej Formation (OS in Figure 2) have developed continuously and can be found over the Early Cretaceous rocks of the volcanic basement rock but also as underlying or overlying the V1 and V2 volcanites and their epiclastic products (Figure 2). Thick packages of these sediments are particularly well developed in areas lateral to the volcanic centers or in parts of the TMC where no volcanism has occurred. OS are represented by layered to laminated grayish siltstones, marls sandy limestones and calcareous sandstones and contain Turonian–Campanian micro fauna [25]. In Čukaru Peki area, these sediments are laminated grayish siltstones and marls (Figure 2g), up to 250 m thick. The deepest parts of the sediment package in the Čukaru Peki area consist of red siltstone and marl (Figure 2h), which are nowhere more than 20 m thick. OS in the Čukaru Peki area underlay the Bor clastites and overlay the rock package consisting of ME and V1B.

Towards the west of the TMC, the V1 andesite grade into the hornblende-pyroxene- to pyroxene andesite and basaltic andesite – V2 (Ježevica Andesite (Figure 2i) and Osnić Basaltic andesite (Figure 2j), V2O and V2J in Figure 2 [8]). Dark grey to gray rocks of porphyritic texture, characterized by mm sized pyroxene, hornblende and feldspar phenocrysts and has mostly hypocrySTALLINE groundmass. They are predominantly emplaced as submarine extrusive volcanics (lava and hyaloclastic breccia) and shallow intrusions. These volcanic rocks reveal U/Pb zircon ages range of 83-81 Ma (Table 1), but related to andesite or trachyte dykes [4]. They are also stratigraphically interlayered with the above mentioned the Senonian sediments (Oštrej Formation) and are at places covered by their volcano-sedimentary - epiclastic products (Figure 2).

In the northwestern and southwestern part of the TMC occur plutonic rock from monzodiorite and

monzonite to diorite, Q-diorite, granodiorite, syenite and rare gabbro compositions (Valja Strž Plutonite, P2 in Figure 2, [8]). They are grey to dark-grey rocks of hypidiomorphic granular texture and massive structure (Figure 2k). This rock intruded in to the basaltic andesite and andesite, V2 volcanics and surrounding sediments and dated at 83-78 Ma ([4,11] Table1). Mineralization and a large number of morphogenetic types of mineralization in V2 rocks are mainly concentrated in the vicinity of the discovered intrusions, Valja Strž in the northwest and Ježevica in the southwest TMC (Figure 1, P2 in Figure 2). It is characteristic of this part of the BMZ that there are smaller porphyry and epithermal systems (Figure 2l) relatively close to the surface, there are also polymetallic replacements and skarn-type deposits (e.g. Valja Saka, Dumitru Potok, Čoka Kuruga, Valja Strž, Lipa, Čoka Kupjatra, among others (Figure 1 and MP2 in Figure 2, [11,17]). The low-sulfidation Au deposit Zlaće was also discovered here, as well as the Korkan-Bigar Hill sediment hosted Au mineralization [11,30], and also minor occurrences of manganese mineralization interpreted to be related to the VMS/SEDEX type of mineralization [31].

From the Upper Campanian to the Maastrichtian, in the Timok West block, reef sedimentation commenced (Bukovo Formation, [25], Figure 1, BS in Figure 2). At the same time, in the Timok East block, coarse-grained and regressive clastites were deposited (Bor Clastic, [25], Figure 1, BK in Figure 2). This was the period when TMC underwent intensive tectonic uplift, ceased to exist as an active volcanic area, and at the end of this period also as a sedimentation area [26].

The Bukovo Formation overlies the Oštrej Formation. There are moderate bedded siltstones and marlstones overlain by sandy limestones with intercalated layers of claystones rich with benthic foraminifera, rudists, gastropods and corals dated as the Upper Campanian-Maastrichtian age. The age is also supported by the index of planktonic foraminiferal species [25].

The Bor Clastic are polymictic coarse to fine-grained conglomerate (Figure 2m) and sandstone. It is built by pebbles of the Upper Cretaceous volcanites and sediments originated from the TMC, pebbles of the Paleozoic metamorphic and igneous rocks, the Paleozoic sediments, the Jurassic and the Lower Cretaceous carbonate rocks, that originated from the basement of the TMC [32]. The micropaleontological content in the Bor Clastic suggests the Upper Campanian-Maastrichtian age [25,32,33].

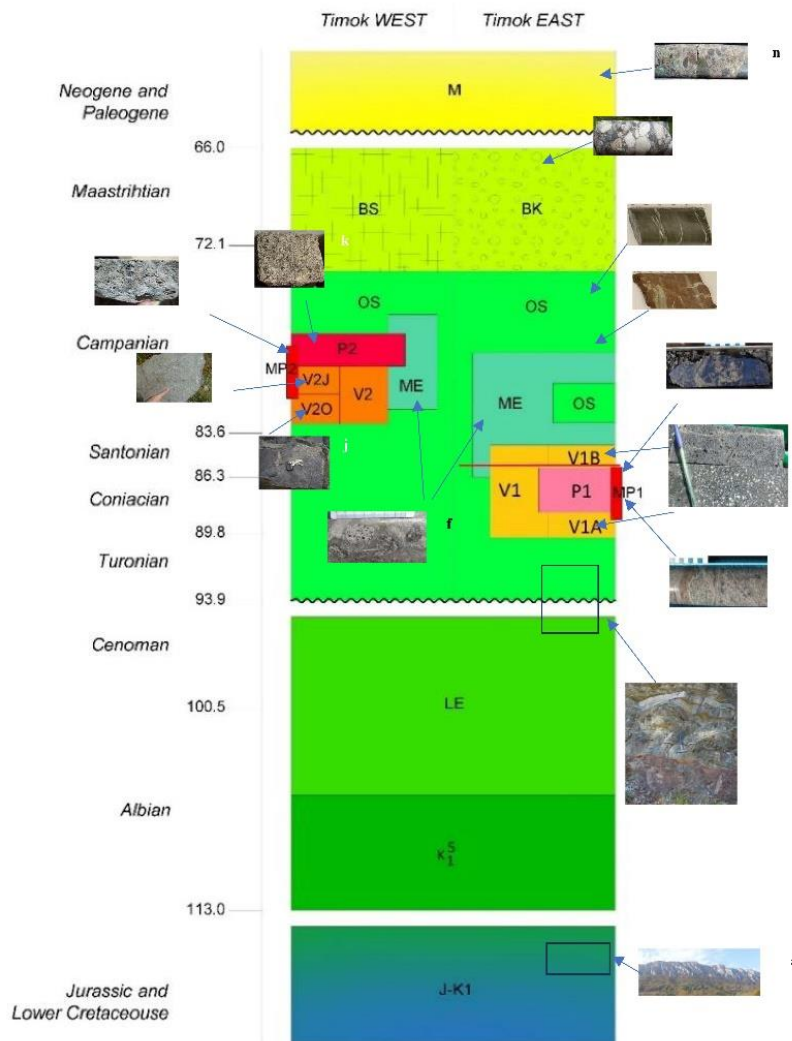


Figure 2 The stratigraphic and time space development of the TMC and the relationship of sediment formations and magmatic suites [8,25,26,27]. On the left side is a schematic stratigraphic chart with epoch and age in million years. LE – Lenovac Formation, OS – Oštrej Formation, V1 – Timok Andesite, volcanic first phase, V1A – Timok andesite sub-phase, V1B – Timok andesite sub-phase, P1 – Shallow intrusions in V1, possible source of mineralization, MP1 – Porphyry mineralization in the Timok East, ME – Metovnica Epiclastite, V2 – volcanic/magmatic second phase, V2O – Osnić Basaltic andesite, V2J – Ježevica Andesite, P2 – Valja Strž Plutonite, MP2 – Porphyry, skarn and epithermal mineralization in the Timok West, BS – Bukovo Formation, BK – Bor Clastic, M – Miocene sediments, Timok EAST – The eastward tectonic block, Timok WEST – the westward tectonic block. The red line highlighted schematic unconformity of the porphyry mineralization in the eastward tectonic block. a) Outcrop of Jurassic-Lower Cretaceous limestone – Veliki Krš Mts. b) Lenovac Formation overbedded by gray marlstone of the Oštrej Formation. The red line highlights the border of these two formations and a clear discordance; c) Comparative macroscopic appearance of fresh hornblende andesite V1B (above) and fresh feldspar rich andesite V1A (below); d) Typical stockwork type of porphyry mineralization in andesite V1A; e) Epithermal, high-sulfidation mineralization in andesite breccia V1A; f) polymictic epiclastic andesite breccia – Metovnica Epiclastic, composed of fresh clasts of V1B andesite and fresh and altered clasts of V1A andesite; g) drill core sample of gray marl – Oštrej Formation; h) drill core sample of reddish marl – Oštrej Formation; i) Greenish gray Ježevica Andesite – V2; j) Dark gray Osnić Basaltic andesite – V2; k) Valja Strž Plutonite; l) Epithermal mineralization in V2 andesite; m) Drill core sample of coarse grained conglomerate – Bor Clastic; n) Drill core sample of coarse grained gravel – part of Miocene sediments

Thinner layers of gray to yellow calcareous-clayey sandstones in to the Bor Clastic are rich in well preserved Maastrichtian spores and pollen [25].

After the big hiatus, new sedimentation cycles started in the Miocene. The Miocene sediments reflect differences in the development in the area of Čukaru Peki and in the area south of Timok. In the area around Čukaru Peki the sediments form the lower and upper parts. The lower part consists of siltstone-clay and marl sediments. The upper part consists of gravel and sand. The greatest thickness of the Miocene sediments around Čukaru Peki is about 300 m. In the area south of Timok, in vertical succession, the Miocene sediments were deposited in different environments: non-marine, marine and brackish ones (from the bottom to the top, [34]).

3. Review of the geochronological age data of rock and mineralization in the BMZ

Geochronological data of the age of rocks and mineralization in the BMZ have been collected for years, published by many different authors and systematically presented in this work (Table 1). The methods for the geochronological age of rocks are U/Pb from separated zircon crystals and Ar/Ar from separated hornblende or biotite crystals, while for porphyry mineralization age are Ar/Ar from separated white mica and Re/Os from separated molybdenite.

Analyzing these data, it can be concluded that the age of the V1 volcanic phase, in different areas of the TMC, correspond from 90.97 to 82.08 Ma [4, 5, 6, 9,12,13].

Table 1 Summary of rock and mineralization geochronological age data in the TMC [4, 5, 6, 9,12,13] zr-zircon, ho-hornblende, bi-biotite, mo-molybdenite, wm-white mica

Location	Lithology	Method	Age Ma	Volcanic phase
Majdanpek	Fresh andesite-dacite	U/Pb zr	85.2±4.2-86.0±7.2 [9]	
Majdanpek-Dolovi	Fresh andesite dyke	U/Pb zr	82.73±0.03 [4]	
Majdanpek-Tenka	Polymetallic mineralization	Re/Os mo	83.37±0.4-83.77±0.5 [7]	V1
Majdanpek-Tenka	Polymetallic mineralization	Ar/Ar wm	83.15 [5]	
Veliki Krivelj	Altered andesite dyke	U/Pb zr	86.17±0.15-86.29±0.32 [4]	
Veliki Krivelj	Andesite dyke	Ar/Ar ho	85.5±1.3 [5]	
Veliki Krivelj	Porphyry mineralization	Re/Os mo	87.88±0.5 [7]	
Bor	Unaltered andesite	Ar/Ar ho	83.4±1.7-84.6±1.1 [6]	
Bor	Unaltered andesite	Ar/Ar bi	89.0±0.6 [5]	
Bor	Altered andesite	U/Pb zr	82.08±0.08; 85.6±0.11 [13]	
Bor-Borska reka	Porphyry mineralization	Re/Os mo	85.94±0.4-86.24±0.5 [7]	V1A
Bor-Borska reka	Porphyry mineralization	Ar/Ar wm	86.3±1-86.9±1.1 [6]	V1
Čukaru Peki	Unaltered andesite	U/Pb zr	85.03±0.09 [13]	
Čukaru Peki	Mineralized andesite	U/Pb zr	86.5±0.13; 88.25±0.28 [13]	
Nikoličevo	Unaltered andesite	U/Pb zr	89.49±0.42-90.97±0.39 [12]	
Gamzigrad	Unaltered andesite	U/Pb zr	88.6±8.0 [9]	
Lenovac	Volcaniclastic	U/Pb zr	89.9±6.0 [9]	
Nikoličevo	Fresh andesite	U/Pb zr	84.89±0.75-85.56±0.53 [12]	V1B
Krivelj	Fresh andesite	U/Pb zr	84.66±0.5 [4]	
Brestovac cross road	Trachyte dyke	U/Pb zr	81.79±0.5-82.27±0.35 [4]	
Podgorac	Basaltic andesite	U/Pb zr	80.8±4.8 [9]	
Valja Strž	Monzonite	U/Pb zr	78.62±0.44 [4]	
Valja Strž	Granodiorite	U/Pb zr	78.9±5.2-82.2±5.4 [9]	
Valja Strž	Diorite	U/Pb zr	78.5±1.3-82.5±0.4 [11]	V2
Čoka Kuruga	Diorite	U/Pb zr	83.6±0.5 [11]	
Cmi Vrh	Diorite	U/Pb zr	80.8±0.6 [11]	
Dumitru Potok	Diorite	U/Pb zr	82.1±0.7-82.2±1.2 [11]	
Dumitru Potok	Porphyry mineralization	Re/Os mo	80.69±0.4-80.82±0.45 [7]	

The age of fresh or altered rocks that can be confidently claimed to belong to the V1A volcanic sub-phase, in the area of Veliki Krivelj, Bor, Čukaru Peki and Nikoličevo generally correspond from 90.97 to 85.03 Ma [4,5,12,13], except for one sample of andesite from the Bor deposit drill hole that shows a drastically younger age of 82.08 Ma [13]. An unmineralized andesitic dyke from the Dolovi area, north of Majdanpek has a similar age (82.73 Ma, [4]). The possibility that these two samples belong to andesites of the V1B sub-phase cannot be ruled out. A trachyte dyke near Brestovac as intruded into basaltic andesite of the V2 volcanic phase have a similar age too (82.27-81.79, [4]).

The porphyry mineralization and the fresh-unmineralized and altered andesitic host rocks associated with the V1A volcanics in the Veliki Krivelj and Bor deposits clearly correspond (Table 1). The age of porphyry mineralization on molybdenite sample from the Veliki Krivelj deposit shows an age of 87.88 Ma [7], while the age of mineralization in the Bor-Borska Reka deposit takes place between 86.9-85.9 Ma [6,7]. Polymetallic mineralization in the Tenka deposit, north of Majdanpek, is younger and amounts to 83.77-83.15 Ma [5,7]. The age of the epithermal mineralization has not yet been determined, but it is most likely younger than the porphyry mineralization.

Unmineralized andesites of the V1B sub-phase from the area of Krivelj and Nikoličevo villages are clearly younger than V1A andesites and their age range from 85.56 to 84.66 Ma [4,12].

There is not much age data for the volcanic rocks of the V2 phase. But, the age of Valja Strž Plutonite which is dated 83.6-78.6 Ma is much better documented [4,9,11]. Volcanites V2 phase and the Valja Strž Plutonite are host rock of copper porphyry mineralization related to diorite porphyry cluster to which the deposits and occurrences on Crni Vrh belong (Valja Strž, Dumitru Potok etc. [17]). The age of the porphyry mineralization at Dumitru Potok deposit range between 80.82-80.69 Ma [7] and clearly corresponds with Valja Strž Plutonite.

4. Conclusion

The review of the stratigraphy, the time space development, the relationship of sediment formations and the magmatic suites and available geochronological age determinations of the TMC rocks and the BMZ mineralization imposed the following conclusions:

- After a generally uniform development from the Early Jurassic to the Lower Cretaceous, during the

Upper Turonian to the Senonian, area of the TMC shows a significant difference in evolution between the eastward (Timok East) and the westward (Timok West) tectonic block. The sedimentation and magmatism continued throughout nearly the whole Late Cretaceous and developed different sedimentary formations and igneous suites (see Figure 2).

- The volcanism/magmatism occurred in at least two phases from the Upper Turonian to the Upper Campanian: V1 (90-82 Ma), V2 (83-78 Ma). The available geochronological ages and volcanological analyses reveal that the I volcanic phase - V1 can be split into two sub-phases: V1A and V1B. The Timok andesite V1A is older (90-85 Ma) and the V1B is younger (85-83 Ma). The V1A sub-phase is associated with mineralization and V1B is clearly postdates the main porphyry mineralization event in the eastern margin of the BMZ.
- The porphyry mineralization in the BMZ ranges widely from 87-80 Ma and the age of the epithermal mineralization has not yet been determined, but is most likely younger. The major epithermal and porphyry mineralization situated along the eastern margin of the BMZ and this metallogenetic zone is probably one of the most prospective areas in Europe for exploration. The discovery testifies that even old and presumably well-investigated mining areas may host significant ore deposits that await to be found, in particular in deeper parts of the existing systems.

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PREGLED STRATIGRAFSKIH KARAKTERISTIKA I STAROSTI STENSKIH JEDINICA U BORSKOJ METALOGENSKOJ ZONI (TIMOČKI MAGMATSKI KOMPLEKS)

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Izvod

Ovaj rad prikazuje stratigrafske karakteristike i starost glavnih stenskih jedinica i vezu između magmatskih procesa, mineralizacije i orudnjenja u Borskoj metalogenetskoj zoni (BMZ) - Timočki magmatski kompleks (TMK). Postojeći, višedecenijski podaci o geološkim istraživanjima u ovoj oblasti dopunjeni su najnovijim podacima sistematskih geoloških istraživanja dobijenih primenom najsavremenijih istraživačkih metoda. Timočki magmatski kompleks se razvija na kontinentalnoj kori izgrađenoj od različitih stena paleozojske do donjokredne starosti i čine ga vulkanske/magmatske, vulkanogeno-sedimentne i sedimentne stene. Sedimentni procesi se u kontinuitetu mogu pratiti kroz čitavu gornju kredu, od alb-cenomana do mastihtu, dok vulkanizam/magmatizam traje oko 10 miliona godina, dok vulkanski produkti bivaju mlađi od istoka prema zapadu. Vulkanizam se može podeliti u dve glavne faze koje traju od gornjeg turona do gornjeg kampana: prva vulkanska faza - V1 (90-82 miliona godina) koja dominira u istočnim delovima TMK i druga vulkanska faza - V2 (83-78 miliona godina) koja izgrađuje centralne i zapadne delove TMK. Najznačajnija ležišta bakra i zlata vezana su za prvu vulkansku fazu, a starost do sada otkrivene porfirne i epitermalne mineralizacije je u rangu od 87-80 miliona godina.

Ključne reči: Borska metalogenetska zona, Timočki magmatski kompleks, stratigrafija, vulkanizam, starost, mineralizacija.

OPPORTUNITIES AND CHALLENGES WITH THE PROTECTION OF ANCIENT MINING SITES IN MOUNTAIN LANDSCAPES: A CASE STUDY OF THE KOPAONIK

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Abstract

The remains of ancient mining activities represent a significant part of Serbia's archaeological sites in the mountain landscapes, which are not yet officially treated as cultural heritage. This type of assets poses a significant challenge for cultural heritage protection services, as it requires co-operation between experts for the protection of natural and cultural values and other stakeholders, which is not yet established. In addition, the concept of mining landscapes is not recognized in current legislation, which further complicates the legal protection of the remains of ancient mines, which are recognized by scholars as an essential segment in the interpretation of historical processes of significance, such as Roman imperialism in the Balkans. Against this background, the paper presents the decades of archaeological research at Kopaonik, which has led, among other aspects, to an attempt to establish a uniform practice of treating ancient mines, together with settlements and associated infrastructure, as an integral part of the mountain landscape, despite the absence of any legal regulation. The study examines the challenges associated with the formal-legal preservation of sites with historic mining, taking into account the possibility of permanent destruction. Finally, an outlook is given on the future of the protection of (pre)historic mines in Serbia as an important element of the country's geocultural resources.

Key words: Kopaonik, antiquity, mining, geocultural heritage, legal regulations.

1. Introduction

Archaeological sites with remains of ancient mining activities represent challenging heritage because they typically occupy large areas, are often located in remote and difficult-to-access locations, and almost always require extensive work for research, presentation, and maintenance [1]. The early twentieth century was notable as the beginning of the initial promotion of sites with mining and metallurgical heritage as a novelty in cultural heritage protection practices of developed European countries. That was mainly contributed to the development of industrial archaeology in the second half of the 20th century, which brought this type of site into focus for research and presentation. Such a situation is most prevalent among countries rich in ancient mining and metallurgical sites, such as Spain, Portugal, France, and others. The preservation of this type of site focuses primarily on recognizing mines as industrial complexes that document technical and technological advances during a given period or continuum. The presentation

often focuses on touring parts of mining facilities that are supposed to depict aspects of ore extraction and mineral processing. In this approach, there is a complete abstraction from the social and physical involvement of the people who lived and worked in these mines [1]. That often happens because archaeologists interpret elements of mining as part of technological progress and development, either in a specific community, region, country, or even humanity. A socially focused interpretation can counteract such a positivist approach by depicting mining and metallurgical relics as part of a specific mining community's experience. However, these initiatives are often dismissed as problematic and ineffective [1, 2]. Consistent with that, archaeological studies of mining sites primarily track technological processes [1], both internationally and locally. However, how study results are understood and communicated to the general public is critical to safeguarding the mining legacy. Indeed, this type of heritage cannot be attributed solely to historical and architectural values; it may also reflect the political

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or ideological background of the historical period in which it originated [3]. The mine workings also contribute to the constitution of a broad complex of cultural landscape characteristics significantly transformed by human activities [4], known as a *mining landscape* [5]. The extraction of mineral resources at a particular place is also associated with a certain lifestyle and the emergence of a particular social and cultural environment [6]. After the cessation of mining activities, the question arises of how to deal with the remaining sites with their various characteristics and phenomena, which at this point become part of the natural and cultural heritage. Furthermore, mining and metallurgy continue to be vital sectors of the modern economy. On the other hand, the material remains of older mining activities (such as shafts, underground tunnels, adits, spoil heaps, open pits, and others) are considered unsightly landscape features, and there have been attempts in the past to remove these traces. However, in recent decades, the attitude towards these material remains (that have persisted to this day and preserved cultural values) has changed, leading to their candidacy for protection as a geocultural heritage. The low attractiveness of mining objects resulting from different standards of aesthetics is another factor one must not neglect [7]. Additionally, the relationship between heritage protection services established by the government, modern geologists and miners, local communities, and other stakeholders in the heritage safeguarding process is an important issue deserving separate consideration.

Since the founding of Serbia's Cultural Heritage Protection Offices, the remains of ancient mining operations are yet to be dealt with as cultural heritage. Although the scientific interpretation of past societies, from prehistory to the present, has recognized the importance of ancient mining, systematic archaeological investigations of mines, which would follow the achievements of historiographers, have yet to be undertaken. Nonetheless, an isolated example of systematic research at the archaeological site of Rudna Glava near Majdanpek, done between 1968 and 1989, discovered the world's earliest dated copper mine to date [8]. This sensational discovery followed the excavation of artefacts of early copper metallurgy from the Neolithic period, i.e. the Vinča culture dated between c. 5400 and 4400 BC. In addition to the first known processing of copper metal from the Vinča culture site of Belovode [9, 10] the metalsmiths at the time also produced the earliest known tin bronze and lead [11,

12]. The mine of Rudna Glava appeared to have been used infrequently in the Late Eneolithic and during the Late Roman period (4th-5th centuries AD) [8, 13]. Despite the scientific interpretation of the first mining and metallurgy, it undoubtedly affected a complete shift in the understanding of the Neolithic period and, by extension, the history of civilization; the physical and legal protection and exhibit of these sites were never implemented [8]. After almost twenty years since its great discovery, Rudna Glava was placed under state protection in 1981 as an immovable cultural property - an archaeological site ("The Official Gazette of the municipalities of Boljevac, Bor, Zaječar, Kladovo, Knjaževac, Majdanpek, Negotin, and Sokobanja" No. 10 dated July 25, 1981) of outstanding importance to the Republic of Serbia ("The Official Gazette of the Socialist Republic of Serbia" No. 28/83).

Despite the comprehensive legal protection, stakeholders have yet to make additional efforts to showcase Rudna Glava as an integral part of our cultural heritage. Even though Serbian archaeology produced evidence of the earliest prehistory mining, further archaeological excavation of mining sites began at the beginning of the last decade. During this period, the Prijuša-Mali Šturac mines on Rudnik Mountain and Jarmovac near Priboj, dated in later phases of prehistory, started to be excavated.

Archaeological research represents the sole source of information for prehistoric studies. For antiquity and the Middle Ages, a dozen written sources convey significant data regarding the mining activities in our regions. Although historical mines have never been directly examined, the outcomes of mining settlements and associated infrastructure excavations have validated and indirectly enriched our understanding of the subject.

In the past decade, there have been thematic archaeological investigations of ancient mines, and there has also been a slight shift in their protection and presentation. The subsequent text presents the author's decade-long engagement in studying and attempting to protect the geoarchaeological remains, exemplified by the mountain of Kopaonik.

It is accompanied by an introduction of the broader context of the Roman organization of provincial mining in the Central Balkans, aiming to provide a comprehensive understanding of the significance of this heritage for the interpretation of ancient history related to the Roman province of Upper Moesia, or the Central Balkans region.

2. Roman Mining at Kopaonik

When examining the ancient topography of the Central Balkans, it is clear that mining sites have concentrated in mountainous areas such as Mount Kopaonik, Avala, Kosmaj, Stara Planina, and other mountains. The accompanying urban and rural structures developed around these areas, forming the imperial mining domains (Figure 1). Detailed information about the administrative organization and functioning of such territories can be obtained from the text of the mining law *Lex metallis dicta*, inscribed on a bronze tablet during the reign of Hadrian, found in the imperial silver and copper mine of Vipasca (Aljustrel, Portugal) [14]. Numerous archaeological excavations have been conducted in the Republic of Serbia since the mid-20th century, uncovering material remains of this process throughout the province of Upper Moesia. As a result, a meaningful number of sites where mining and metallurgical activities took place during the Roman period are known to archaeologists. Some sites have been partly preserved and presented to the general

public, such as Timacum Minus, Ulpiana, Remesiana, Municipium DD, Kraku Lu Jordan, and others. These sites have been recognized as urban, defensive, or administrative features in the mountainous landscape, containing functional structures related to mining and metallurgical activities. However, the remains of ancient shafts, open pits, underground galleries and tunnels, other mining structures, as well as numerous smelting sites with furnaces and slags have received no cultural heritage protection, either as part of the landscape surrounding the ancient mining settlements or as separate cultural assets. The only exception refers to Mount Kopaonik and the Zaječak site, where the remains of metallurgy from the 3rd and 4th centuries have been discovered (Figure 2). The site has been recognized as a bearer of cultural values and is protected as an immovable cultural property - an archaeological site ("The Official Gazette of the Republic of Serbia" No. 2/2003). While legally protected, this property has never been preserved nor presented to the general public.

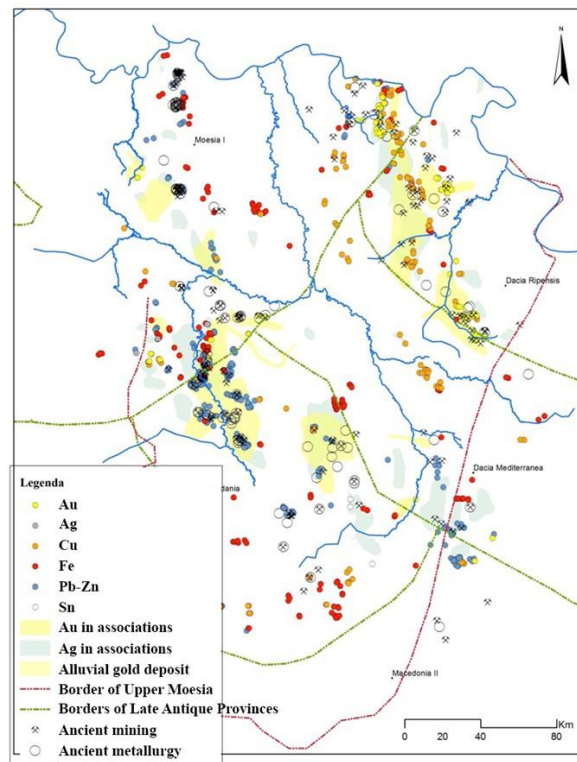


Figure 1 The mineral potential of the Central Balkans with mining and metallurgical sites of the antique period [15]



Figure 2 The remains of metallurgical furnaces at the Zaječak site in Kremiči, Kopaonik (Archive of the National Museum in Kraljevo)

The existing archaeological research on ancient sites in Kopaonik undoubtedly testifies to the inseparable connection between cultural heritage and the mineral wealth of this mountain. As ore partly dictated the political strategy of the Roman Empire, Kopaonik (as a significant Dardanian mining district) became part of the imperial domain *Metalla Dardanica* within Upper Moesia province. The products from these provincial mines (lead ingots) were encountered throughout the whole Empire, from the Tiber in the west [16, 17] to Caesarea Maritima in the east [18]. In addition to the discovery of lead ingots with inscriptions about the metal's origin, lead isotope analyses have recently been conducted, confirming the use of metals from the Kopaonik region, primarily from the area of Novo Brdo, for the construction of the fort and, lately, the town of *Novae* in the province of Moesia Inferior (Northern Bulgaria) in the 2nd-3rd centuries [19]. Although mining was extensive across the mountains of Kopaonik during Roman times, the following evidence will focus on the area of the Suvo Rudište mine with remains of metallurgy at Metodje, Trsove Bare, and Zaječak, as well as the archaeological site of Nebeske Stolice.

The geoarchaeological complex of Suvo rudište, located in the flat part of Kopaonik below the Pančić Peak, is the largest area containing the remains of mining on the territory (Figure 3). This location is part of the Belo Brdo mine, situated on the administrative boundary between the Autonomous Province of Kosovo with Metohija and Serbia. The recent mine's main shaft lies near Leposavić, and ore was mined underground in the municipalities of Raška and Brus. In this mine, magnetite was actively exploited until the 20th century,

leading to the destruction of older remains of iron and copper ore exploitation. However, archaeologists have discovered traces of earlier mine workings across the entire mining zone. To the east and southeast of Suvo rudište lies a broad ore-rich area covered with several ancient workings (mainly small pits), grouped around Caričina Strana, Vojetina, Kamenica, Belo Brdo, Marušići, and Zaplanina. On Caričina Strana, a series of pits continue northeast for several hundred meters, while in Marušići, they occupy few hectares. At a slightly lower elevation, in the area of the National Park, within the territory of the village of Šipačina, lies the metallurgical site of Trsove bare.



Figure 3 The remains of former mining activities at the Suvo rudište site at Kopaonik

During a recent field survey, we found several smelting furnaces and some artefacts from the 3rd and 4th centuries. We have identified this site as an archaeometallurgical complex similar to Zaječak. Further, a part of a well-known hiking trail that leads to the sanctuary in the rock dedicated to St. Methodius is an archaeological site of Metodje (Figure 4).



Figure 4 The ancient mining shaft (after archaeological excavation) in the hiking trail at the Metodje site at Kopaonik

In August 2022, the first thematic archaeological excavation was conducted at Metodje under the leadership of the author of the paper on behalf of the Institute for the Protection of Cultural Heritage in Kraljevo, financed by the Ministry of Culture of the Republic of Serbia. The research has shown the existence of mining shafts and roads with preserved wooden structures, a metallurgical furnace, and areas for the purification and smelting of ore. Unfortunately, temporally sensitive archaeological material was not found, so the site is dated approximately to antiquity or the Middle Ages.

This brief overview of historic mining and metallurgical activity at Kopaonik was provided to illustrate the geocultural space, where all accompanied ancient settlements are located on flattened river terraces at the foot of the mountain (Figure 5).

The only architectural structure found within the Suvo rudište area is the remains of an Early Christian church at Nebeske Stolice, which represents the most recognizable part of the cultural heritage of the mountain (Figures 5. and 6). St. Procopius is remembered not just as a great martyr who suffered under the reign of Diocletian but also as a protector of miners, even though the buildings were buried centuries ago. The Institute for the Protection of Cultural Heritage in Kraljevo conducted a detailed exploration of this site during several campaigns from 1998 to 2010. The results of these investigations have confirmed the belief that the church preserves the remains of a sacred building from the 5th-6th century and a late Roman (military?) structure from the 3rd-4th century period. The fragments of frescoes that were discovered in the debris layer and polychrome mosaics on the floor testify to the past representativeness of the Early Christian church preserved only in the foundational zone and the lower level of the walls (Figure 7). The mosaic was crafted using the opus tessellatum technique and composed of panels depicting geometric and zoomorphic motifs. Fragments of window glass were discovered on the mosaic floor, indicating that light formerly reached the building's interiority, playing a specific role in the entire experience of the sacred in Christianity. At Nebeske Stolice, every liturgical detail was meticulously attended to, as evidenced by the perforated cross once belonging to the polyeleos. Archaeological excavations at this site have also uncovered an earlier phase of life, manifested in a late antique structure where coins of Roman emperors from the 3rd and 4th centuries were found, along with fragments of ceramic and military equipment,

glass vessels, jewelry, tools, slags, and other artefacts [20]. According to the archaeological findings, the older architectural structure operated as a small military point within the mining district. The site is surrounded by many small mining pits, concentrating in significant numbers southeast of the site [15], which spread further into the whole area of Suvo Rudište.

This topographic representation of ancient Kopaonik (Figure 6) is a chronologically unique, functioning microcell within the mountain landscape. Skipping any element threatens the interpretation of Roman provincial history, affecting the imperial domain *Metalla Dardanica* and the entire province of Upper Moesia. To identify places with legacy value, we examine them against specific criteria to discover potential heritage assets. The valorization of material remains must enhance the understanding of cultural properties to secure formal legal protection for specific places within the historic mining landscape. Furthermore, it is necessary to create presentation models with long-term contexts to ensure this property's preservation and maintenance.

3. The Current Practice in Protecting the Mining Heritage and New Challenges

The realm of cultural heritage protection, with established services within a state, constitutes, both technically and symbolically, an entity responsible for preserving all material and immaterial traces of the past, indirectly safeguarding the uniqueness of tradition and the recognisability of the cultural identity of peoples and spaces across every segment of history. The outcomes of the valorization process, the establishment of formal legal protection, and the presentation of cultural heritage should depict the past in its diverse spectrum and highlight each of its segments. This process largely depends on the degree of academic focus on specific archaeological phenomena and interpretations of historical currents, often resulting in an unrealistic depiction. The value of Serbia's antique cultural legacy reflects this situation thoroughly.

The importance of the Central Balkans *Res Metallica* for the economy of the Roman Empire, as well as the fact that mining constituted the backbone of the Upper Moesia economy, was first emphasized by S. Dušanić in numerous works dedicated to this topic [21]. However, archaeological research has not adequately followed the findings of historians on this topic. The materialization of the remains of these processes has remained untreated by the heritage protection services.

In addition to the lack of archaeological research on sites with mining content, there is also a lack of valorization regarding natural and cultural values [22]. These are essential material remains with multiple values that are not listed as immovable cultural or natural heritage. The reason for this lies in the fact that

mining sites are attributed to geoheritage by their nature, and in terms of protection, the fact that a mine becomes cultural heritage at the time of ore exploitation is neglected, leading to an intertwining of two approaches to security - nature and culture.

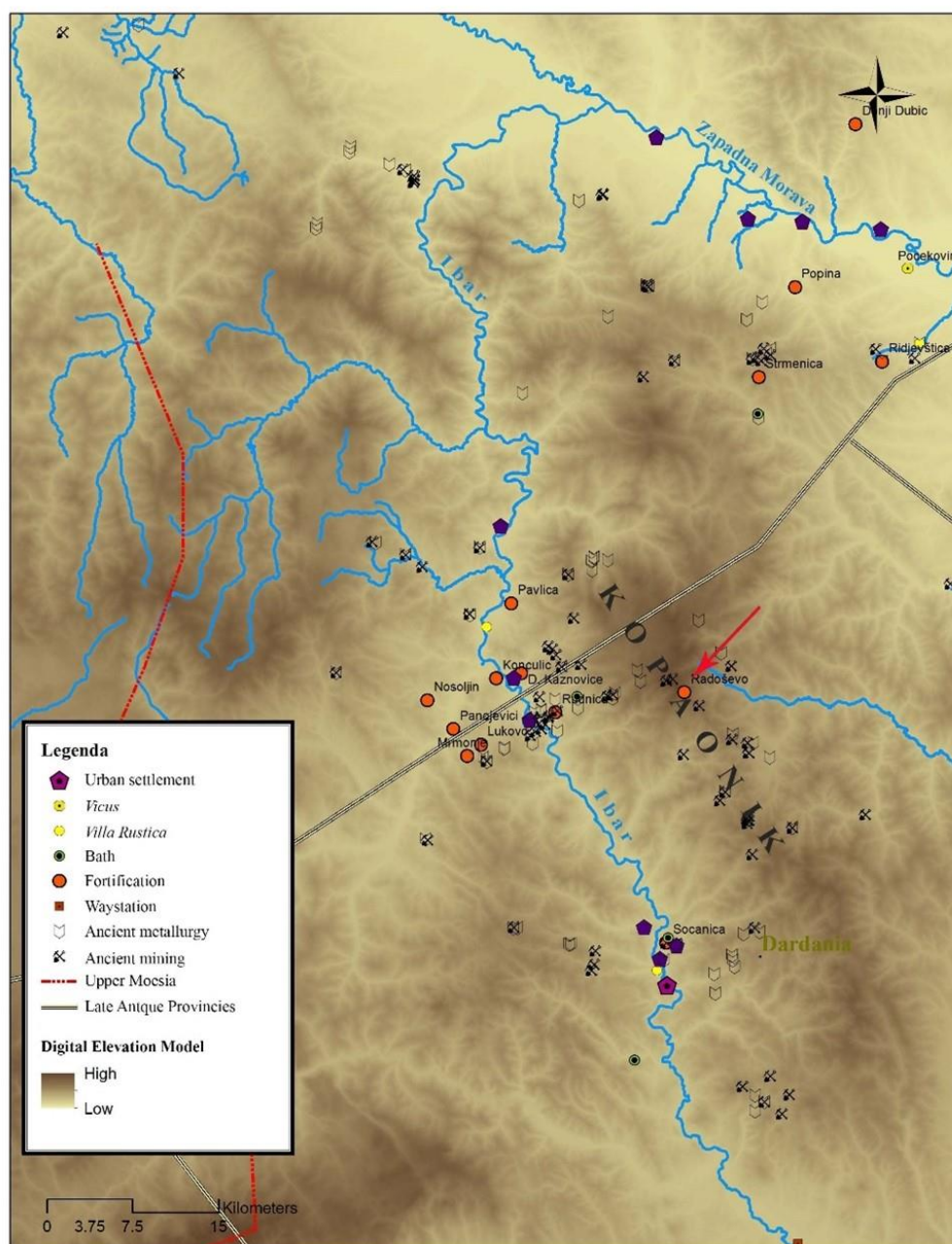


Figure 5 The Roman period sites across the broader area of Kopaonik and the position of the Nebeske Stolice



Figure 6 The location of the Nebeske Stolice site at Kopaonik (Photo by D. Anđelković)



Figure 7 The remains of the floor mosaic of the early Christian church at the Nebeske Stolice site at Kopaonik (Archive of the Institute for the Protection of Cultural Heritage in Kraljevo)

The recognition of the significance of mining and metallurgical remains in cultural heritage protection begins with the UNESCO *Recommendation concerning the Preservation of Cultural Heritage* of 1976. Article 3 of this recommendation states that *the cultural or natural heritage should be considered in its entirety as a homogeneous whole, comprising not only works of great intrinsic value but also more modest items that have,*

with the passage of time, acquired cultural or natural value [23]. This is followed by the *European Landscape Convention* adopted in Florence in 2000, and ratified by Serbia in 2011. After establishing the acts mentioned above, there is a gradual shift in the treatment of sites with remains of mining activities as they are first incorporated into spatial planning documents. However, they never acquire the status of cultural assets. That is due to a need for more support within the domestic legal framework, namely, a lack of harmonization among legal acts. In December 2017, the Ministry of Environmental Protection adopted the *Regulation on Criteria for the Identification of Landscapes and the Assessment of their Significant and Characteristic Features* ("The Official Gazette of RS", No. 119, dated December 29, 2017). As the main criteria for identifying landscapes, Article 3 of this Regulation defines *Cultural characteristics* as the spatial representation of cultural heritage, which includes changes in the environment caused by human interaction with space over time, forming a unity with the works created and traditions inherited from past values, and including immovable, movable, and intangible cultural heritage. At the same time, the Law on Cultural Properties ("The Official Gazette of RS", No. 71/49, 52/2011 – other laws, 99/2011 – other laws, and 6/2020 – other laws) does not recognize the concept of cultural landscape. Furthermore, the absence of archaeological research on ancient mines also diminishes the possibility of valorizing material remains, leaving these sites still under the protection afforded by existing legislation.

The issues addressed in this work stem directly from the conservation service's everyday practices. While preparing the documentation for the designation of the site of Nebeske Stolice on Mount Kopaonik, a series of technical and administrative obstacles have arisen related to establishing a protected area around the site and acquiring official documentation for that area. As mentioned earlier in the text, the architectural remains of an early Christian church from the 5th to 6th century and the military facility from the 3rd to 4th century are located high in the mountainous landscape of Kopaonik within the Suvo Rudište mining area (Figure 6). It is a unique mountainous mining landscape that cannot be treated as a landscape in legal protection because the current Law on Cultural Properties does not recognize that category. Instead, the site is defined as an archaeological site with protected surroundings. Therefore, the site of Nebeske Stolice is located directly below the Pančić Peak, at an altitude of 1800 meters.

It is the only example of a systematically researched site on Kopaonik and possesses complete, legally prescribed archaeological documentation. All immovable architectural remains are located on a single parcel within the cadastral municipality of Ravnište (the city of Brus), adjacent to the administrative border with the Autonomous Province of Kosovo and Metohija. The landscape to which the site belongs spatially and functionally is the mountainous mining district of Suvo Rudište. Within this district, numerous remains of ancient mining activities from various periods are evident in the terrain (Figure 8.).

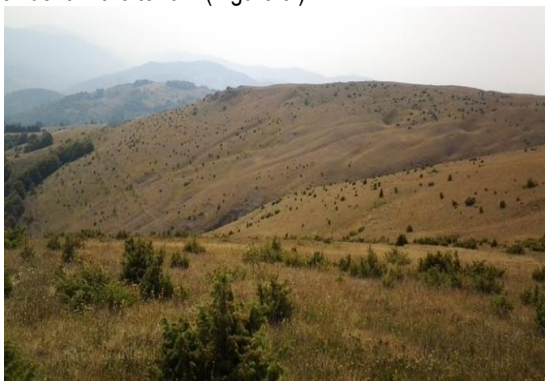


Figure 8 The remains of ancient mine workings near the site of the Nebeske Stolice at Kopaonik

However, an archaeological investigation is yet to be conducted, which makes it problematic to attribute a chronological structure to these remains. In any case, they all belong to the same landscape, spanning two modern administrative units. This situation represents a specificity of this site due to the current political reality, which has resulted in a dual administrative arrangement of the authorities in Kosovo and Metohija.

The official stance of the Republic of Serbia is that Kosovo and Metohija remain an integral part of the state; thus, from that perspective, the site does not have a cross-border character. On the other hand, the relevant Institute for the Protection of Cultural Heritage in Priština, currently situated in Leposavić has recently not been engaged in preparing immediate surroundings to be declared a cultural asset due to the province's unstable political situation.

Preparing a proposal to designate only the area belonging to the municipality of Brus territory as a cultural property, for which cadastral data are available (Figure 9), appears to be an inadequately defined situation. After considering the site's immediate surroundings, we have concluded that it is necessary to

include at least the entire plateau where the architectural structures are and nearby remains of small pits preliminarily identified as antique.

The part of the plateau and the whole mining site are spatially/cadastrally located within the province's territory and belong to a vast parcel for which, due to technical reasons, a cadastral plan cannot be obtained from the cadaster office in Leposavić. So, the case has reached a dead end, even without considering the further issues of other mining and metallurgical locations at Kopaonik that deserve to be declared as cultural heritage, which also occupy their place in the same landscape.



Figure 9 The position of the archaeological site of the Nebeske Stolice with protected surroundings (source <https://a3.geosrbija.rs/>)

The epilogue of the Nebeske Stolice case is the completed documentation ready for declaration, thanks to the proposers' perseverance in their intention to obtain the status of immovable cultural assets for this site, along with its mining landscape. The proposal for declaration has been submitted to the relevant Ministry of Culture of the Republic of Serbia, which will conduct further procedures and submit it to the Government of the Republic of Serbia for decision-making.

4. Discussion

Kopaonik, the most famous tourist center in the Republic of Serbia, presents an intriguing destination for potential investors who want to develop tourist complexes and associated amenities. Furthermore, the Suvo Rudište mine, despite being exploited for centuries, still possesses a significant ore deposit, an essential resource for the state's economic development. Therefore, the state's economic interests and potential activities conducted in that regard, focused

on the area of Kopaonik, pose a potential threat to the destruction of the cultural landscape of Kopaonik, including significant traces of ancient and medieval history [24]. The fact that this mountain has a long history of ore exploitation has resulted in locally diverse mining heritage, both chronologically and typologically. What becomes apparent from this is the importance of researching and analyzing the material remains of mining in the context of the time it originated. Proclaiming the site as an immovable cultural property is only the first step in its protection and prevention from potential devastation. However, it is essential to continue the conversion of assets to other purposes (e.g. tourism), where discussing the methods of identification, management, and interpretation of local mining heritage is crucial. This way, cultural heritage becomes an economic resource, and the tourist offer gains new value.

On the other hand, the situation becomes complicated due to the potential resumption of mining activities at Suvo Rudište. Reopening the mine and organizing sustainable development of the geocultural heritage in the same area pose a significant challenge to conservation services in devising their functional synergy (if possible at all). In that regard, in addition to archaeological investigations of the remains of ancient workings, it is necessary for companies conducting geological surveys to provide relevant Institutes with data on those remains. These companies are obliged to document these works to create a study on the protection of geohistorical heritage (Articles 18 and 19 of the Law on Mining and Geological Research "The Official Gazette of RS", No. 101/2015, 95/2018 – other laws 40/2021). Given that the law above does not stipulate that these studies be submitted to relevant cultural heritage protection institutions, this must be formulated through legally binding Conditions issued by the Institutes to investors to obtain permits for research. In this way, the heritage protection service's database will be augmented, providing a better understanding of the type, quantity, and extent of ancient mining works. The existence of such a database would facilitate the creation of an integrated strategy for the protection of geocultural heritage, namely cultural heritage that constitutes an integral part of ancient mine workings, as exemplified by the situation presented on Kopaonik and known on other mountains in Serbia where mining exploitation in (pre)historical periods was confirmed.

Furthermore, it is essential to emphasize that a shift has been made in the Republic of Serbia regarding the

protection and presentation of ancient mine workings by declaring the prehistoric copper mine Prjuša at the Rudnik site an immovable cultural property - an archaeological site ("The Official Gazette of the Republic of Serbia" No. 13 dated February 24, 2017). The results of archaeological excavations at the Prjuša site until 2017 and their interpretation provided solid arguments for valorization, thereby confirming its significance. The size of the mine and the extent of the documented ancient works designate it as the largest known prehistoric copper mine in Southeastern Europe. The findings of metal from the Dolnoslav site in southern Bulgaria testify that the raw material for toolmaking originated precisely from Rudnik [25], indicating a complex network of routes and an advanced exchange and trade system during prehistoric times. The scientific, expert, and heritage significance of this site paved the way for legal protection despite being located within the active mining landscape of Mount Rudnik. The on-site presentation and adequate media outreach have contributed significantly to the site's accessibility to the broader public (Figure 10). Consequently, it is now the sole example of conserving prehistoric mines in Southeastern Europe.



Figure 10 The archaeological site of Prjuša on Rudnik as it appears today (Archive of the Archaeological Institute in Belgrade)

The study presents a continuation of good practice in systematically treating ancient mines as part of Serbia's geocultural heritage. It focuses on the ancient mining landscape of Suvo Rudište with Nebeske stolice on Mount Kopaonik. Despite the current political challenges, it has been proposed that the site be declared an immovable cultural property - an archaeological site. After submitting the proposal for the declaration of the site as a cultural asset to the Ministry of Culture, the legal regulations changed. In 2023, the

new Law on Cultural Heritage of the Republic of Serbia ("The Official Gazette of the RS", No. 129, dated December 28, 2021) came into force, introducing a new category of immovable property: **cultural landscape**. This term refers to *an area resulting from the interaction between culture and nature or humans and their natural environment. A cultural landscape reflects the evolution of human society and settlements over time, sustainable land use practices conditioned by the constraints and characteristics of the natural environment, as well as successive social, economic, and cultural influences, and a specific spiritual relationship with nature*. Indeed, the cultural landscape category encompasses the mining landscape discussed in the previous text, significantly facilitating cultural heritage protection services' systematic treatment of the remains of (pre)historic mining, along with associated settlements and infrastructure. The new law has also introduced a Program for the Protection and Preservation of Cultural Heritage in the Republic of Serbia, which, among many elements, emphasizes priorities for interdepartmental cooperation (scientific research, education, balanced regional development, and international collaboration). This priority fosters interdisciplinary approaches and dialogue among all stakeholders, including miners, cultural and natural heritage experts, local communities, touristic organizations, the state, local authorities, and others. Although this system will take time to be fully established, it is crucial to begin by raising awareness of the significance of the remains of ancient mine workings as part of the Republic of Serbia's cultural heritage.

5. Conclusion

Although Serbia still lacks a formally established procedure for treating ancient mining sites in the sense of valorization and protection as cultural heritage, the example of Kopaonik transcends into a pioneering challenge. If we set aside administrative and legislative challenges, it is essential to open a reflective and philosophical narrative about protecting this ancient heritage.

This approach aims to ensure that numerous mining sites within the Roman imperial domains rightfully bear witness to their significance and function during Roman domination in these regions. Such a practice would follow new scientific achievements that have demonstrated the importance of Balkan mines for the economy of the Empire, placing them on par with renowned mines in Spain, Portugal, Sardinia, and other

parts of the Empire. In doing so, Serbia would secure a new resource for heritage exploitation.

Western European countries have established a sustainable principle of preserving geodiversity by founding and networking geoparks. To declare a specific area a geopark, it must have a geological heritage of international significance, established responsible management involving all stakeholders, organized promotional activities aimed at boosting the local economy, and access to the network of other geoparks. Considering that human interventions on geological structures (mines and quarries) are included under geodiversity, this concept would be enhanced by incorporating cultural heritage alongside a well-designed presentation. Although geoparks seem like an ideal solution for preserving this type of heritage, the question remains whether the geological heritage of all mountains in Serbia meets the requirements for establishing geoparks. The answer to this question will be obtained through systematic research and valorization of natural and cultural values in each case. Suppose the study results and valorization of geodiversity show the impossibility of meeting the criteria for establishing geoparks. In that case, there is always the possibility of protecting this type of heritage through the existing legal regulations of the Republic of Serbia. From all the points above, it is clear that the current legal regulations still need to be revised to improve the work of cultural heritage protection services. In many cases, even the signed and ratified international conventions are either not implemented at all or need to be sufficiently incorporated into laws that deal with cultural heritage. Ultimately, it is vital to preserve the physical integrity of archaeological heritage alongside formal legal protection, even for future generations and regulations. By protecting and conserving geoarchaeological heritage, we are safeguarding the material remains in situ and preserving information as a source of knowledge that has no expiration date.

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MOGUĆNOSTI I OGRANIČENJA ZAŠTITE ANTIČKIH RUDNIKA U PLANINSKOM PEJZAŽU: STUDIJA SLUČAJA PLANINE KOPAONIK

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Izvod

Ostaci antičkih rudarskih aktivnosti iako čine značajan deo arheoloških lokaliteta u planinskim pejzažima Srbije, još uvek se u formalnom smislu ne tretiraju kao deo kulturne baštine. Ova vrsta lokaliteta predstavlja izazov za službu zaštite kulturnog nasleđa jer zahteva saradnju stručnjaka za očuvanje prirodnih i kulturnih vrednosti i svih drugih zainteresovanih strana, što do sada nije uspostavljeno. Pored toga, važeća pravna regulativa ne prepoznaje koncept rudarskog pejzaža, što značajno otežava pravnu zaštitu ostataka starih rudnika, koje je nauka odavno prepoznala kao ključni element u tumačenju rimskog imperijalizma na Balkanu. U tom svetlu, rad predstavlja višedecenijsko arheološko istraživanje Kopaonika, koje je pored ostalog, rezultiralo pokušajem uspostavljanja jedinstvene prakse tretiranja antičkih rudnika, zajedno sa naseljima i pratećom infrastrukturom, kao integralnog dela planinskog pejzaža, uprkos nedostacima zakonske regulative. Studija ispituje izazove u formalno-pravnom očuvanju istorijskih rudnika, uz razmatranje potencijalnih opasnosti koji mogu dovesti do njihovog trajnog uništenja. Na kraju, otvoren je narativ o budućnost zaštite (pra)istorijskih rudnika u Srbiji kao važnog geokulturnog resursa države.

Ključne reči: Kopaonik, antičko rudarstvo, geokulturno nasleđe, zakonska regulativa.

OPTIMIZATION OF MICRONIZING ZEOLITE GRINDING USING ARTIFICIAL NEURAL NETWORKS

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Abstract

The micronizing grinding of natural zeolite, of the clinoptilolite type, was investigated in a ring mill. The aim of the experiment was to determine the optimal grinding conditions to obtain a powder with appropriate physico-chemical and microstructural characteristics that would find its potential application as a binder and ion exchanger in structural composites. The analysis of specific size classes of zeolite e after micronization was performed by grinding kinetics.

The research was carried out on previously prepared zeolite samples, on wider and narrower size classes (-3.35 + 0 mm; -3.35 + 2.36 mm; -2.36 + 1.18 mm; -1.18 + 0 mm) and different starting masses (50 g, 100 g, 200 g). Fine grinding was carried out at different time intervals (20 s, 45 s, 75 s, 120 s, 300 s, 900 s). A sieve analysis was performed on the grinding products, the content of the size class (-5 + 0) μm and the specific surface area of these products were determined. XRD analysis was performed on individual grinding products to take into account possible changes in the zeolite material itself. Based on the results obtained, an artificial neural network was developed and then compared with the experimental results. The artificial neural network models have achieved a satisfactory prediction accuracy (0.989 - 0.997) and can be considered accurate and very useful for the prediction of variable responses.

Key words: zeolite, micronizing grinding, specific surface, artificial neural networks.

1. Introduction

Clinoptilolite is one of the most common natural zeolites, easily obtained from mines [1], and belongs to a wide group of natural and synthetic materials that are characterized by differences in terms of their chemical, physical and structural properties [2, 3]. Natural zeolites are microporous crystals of aluminosilicate composition, a network structure composed of well-defined cavities, interconnected by channels in which cations and water molecules are located. They represent micropores of crystal hydrated aluminum silicates, and their primary or basic building block is the TO_4 tetrahedron (T = Si, Al) in the center of which Si and / or Al atoms are located, while oxygen atoms are located on the forks. These units are connected in space via common oxygen atoms, building secondary polyhedral units whose connection creates a crystal (aluminosilicate) lattice.

Since the aluminosilicate lattice is formed by connecting Si(IV)-O and Al(III)-O building units, it is negatively charged, and electroneutrality is provided by cations of alkali and / or alkaline earth metals located

inside the channels and cavities of the lattice. These hydrated cations are mainly, Na^+ , K^+ , Mg^{2+} and Ca^{2+} and less frequently Ba^{2+} and Sr^{2+} . Due to weak electrostatic interactions with the aluminosilicate lattice, these cations are mobile, and in contact with the solution they are easily exchanged by ions from the solution, which gives zeolites the property of ion exchangers. Zeolites are actually forms of "molecular sieves" connected by micropores and cavities, and due to such structure and manifested ion-exchange properties, zeolites are very often used as sorbers in composite construction materials [4 - 6]. Structural voids in the range of molecular dimensions (3-10 Å) can provide space for cation reception (Na^+ , K^+ , Mg^+ , Ba^+ , Ca^+), and various metal cations, transition metal ions (Co, Fe, Mn, Zn), as well as molecules and ions from the group (H_2O , NH_3 , CO_3^{2-} , NO_3^-) [23]. Water molecules that can be reversibly desorbed are also located in channels and cavities, which gives zeolites the properties of drying agents [7, 8]. The process of micronizing grinding is intended to grind the mineral raw material to particles of micron size and thus

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prepare it for direct application or for further technological processing. The process of micronizing grinding is mainly applied for grinding mineral raw materials that have already been crushed, by crushing and standard grinding. The application of a prolonged micronization procedure in a certain time interval under certain conditions increases the specific surface area of the treated powder, improves the reactivity and pozzolanic activity of the zeolite material, increases the cation exchange capacity and agglomerates the samples [9, 10].

Amorphization, particle size reduction, and agglomeration cause a decrease in crystallinity [11 - 13]. Micronizing grinding is performed under the action of external forces, and primarily, as with standard grinding, it is achieved by splicing surfaces, cracks and other defective places in mineral grains [14]. The main problem related to micronizing grinding at the industrial level is in the sustainability of this procedure in economic terms, so an ideal balance must be found between the achieved properties of the treated material on the one hand and the time and energy consumption for the process on the other.

Recently, artificial neural networks are increasingly used in modeling and optimizing the grinding process. Flament et al. (1993) [15, 24] in their paper considered the identification of the dynamics and reverse dynamics of a simulated grinding cycle, using neural networks. An experimental program was set up to test the management of a simulated industrial grinding cycle using a number of control strategies based on non-feedback networks [15, 24]. Ma et al. (2009) [16] developed a series of artificial neural networks (ANN) for the analysis and prediction of correlations between process parameters and morphological characteristics of nanocomposite WC-18% MgO powders using the backward error propagation algorithm (BP). The prediction results of the BP algorithm showed good coherence with the experimental data, and the optimized grinding parameters were obtained using an artificial neural network and experimental data. They came to the conclusion that the BP algorithm can be applied to grinding processes in high-energy mills [16]. Ahmadzadeh and Lundberg (2013) [17] tested different methods of predicting the wear of the lining from the mill, in the context of the remaining height and the remaining service life of the lining. They applied multiple linear regression and artificial neural networks to determine the most favorable methodology for predicting lining wear [17]. In their second paper, Ahmadzadeh

and Lundberg (2013) [18] attempted to develop a method that predicts the remaining service life of a coating, without the need to stop the mill. Artificial neural networks are designed based on various process parameters that affect the wear of the lining. The results showed an accuracy of 90%, the artificial neuron model was able to predict the remaining service life of the liner while the mill was operating; it is not necessary to stop the mill for any maintenance activity, which prevents large financial losses [18]. Singh et al. (2013) [19] developed a wrestling neural network model to predict the distribution of the granulometric composition of grinding products using available grinding data for different chromite ore grindability. They made a mathematical model that was tested on middle classes of chromite ore. The results showed a comparative accuracy of predictions for all three models, and the value of r^2 varies between (0.76 - 0.93) [19]. Terzić et al. (2017) [8] examined the mechano-chemical activation of bentonite clay in an ultra-centrifugal mill, to obtain a material that is used as a binder and sorbent in building composites due to its physical-mechanical and microstructural characteristics. The activation efficiency of bentonite clay was determined by a chemometric and mathematical model of an artificial neural network. The obtained results using an artificial neural network for observing the process parameters and the quality of bentonite clay were compared with the experimental results. The value of the coefficient r^2 between the experimental data and the data of the artificial neural network model for the content of the size class (- 5 + 0) μm is 0.811 [8]. Terzić et al. (2017) [12] in their second work examined the mechano-chemical activation of natural clinoptilolite-type zeolite from seven deposits in an ultra-centrifugal mill, for the production of powder with appropriate physicochemical and microstructural characteristics that can be used as a binder and ion exchanger in structural composites. An artificial neural network was developed on a mathematical model of the observed responses and then compared with experimental results. The artificial neural network model had 227 exit point models. Experimental results as well as the results of mathematical models showed that zeolite micronized for 30 minutes is optimal for obtaining a powder that can be used as a binder and ion exchanger. At this time of micronizing grinding, 38.8% of the content of the size class (- 5 + 0) μm was obtained. The value of the coefficient r^2 between the experimental data and the data of the artificial neural network model for the content of the size class (- 5 + 0) μm is 0.936

[12]. Farizhandi et al. (2020) [20] used a planetary mill to develop a rapid assessment procedure to identify the characteristics of powders and granular materials. The grinding results in the planetary mill are then introduced into the artificial neural network model to describe the change in the distribution of the granulometric composition caused by the attrition of the particles during fluidization [20]. The modeling of an artificial neural network in this paper aims to optimize the process of micronizing grinding (in order to obtain the shortest time of micronizing grinding, the lowest energy consumption), to obtain materials with the best properties.

This paper aims to test the dry micronization of zeolite, using modern methods to determine the physico-chemical and mineralogical characteristics of micronized zeolite products, and the changes in the parameters that determine the operation of the vibrating mill with rings (grinding time, number of revolutions), as well as the analysis of the quality of the micronizing powder described by numerous parameters (specific surface area, granulometric composition for different size classes, mill filling, etc.) to obtain the finest micronized product with improved reactivity. Based on the obtained micronization results, it will be possible to predict the results using artificial neural networks to determine the best grinding conditions and the optimal product.

2. Experimental part

2.1. Materials

The paper plans to examine the dry micronization of zeolite, using modern methods for determining the physicochemical and mineralogical characteristics of micronized zeolite products, and changes in parameters that determine the operation of the vibrating mill with rings (grinding time, number of revolutions), as well as quality analysis of micronizing powder. Numerous parameters (specific surface, granulometric composition for different size classes, mill filling, etc.), in order to obtain the finest micronized product of improved reactivity. Based on the obtained results of micronizing grinding, the results will be predicted using artificial neural networks, in order to determine the best grinding conditions and the optimal product.

The zeolite sample is gray, while the crystals are lithocrystalloclastic to crystalloclastic. It contains about 90% zeolite, in a smaller amount quartz, feldspar, mica and calcite and traces of illite. Prior to the micronization

grinding process, sample preparation was carried out. The zeolite sample was first crushed in a laboratory jaw crusher to an upper limit size of 3.35 mm. This was followed by homogenization, splitting of the sample and representative sampling. Four size fractions (- 3.35 + 0 mm; - 3.35 + 2.36 mm; - 2.36 + 1.18 mm; - 1.18 + 0 mm) in different starting masses (50 g, 100 g, 200 g) were also prepared and subjected to micronizing grinding. Chemical analysis of the zeolite sample was determined by a standard analytical method. The results of the chemical analysis are given in Table 1 [14].

Table 1 Chemical composition of the initial zeolite sample [14]

Component	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	Lol*
Content, %	64.05	15.29	2.52	4.82	1.33	0.77	1.27	9.86

* Lol - Loss on ignition determined as weight difference between 20 ° and 1000 °C

2.2. Micronizing grinding

Micronizing grinding of zeolite was performed in a laboratory vibrating mill with rings of the type "SIEBTECHNIK TS-250", at a speed of 1000 rpm in a time interval of 20 s, 45 s, 75 s, 120 s, 300 s, and 900 seconds. The content of the size class (- 5 + 0) μm, which was determined using ultrasonic sieve (US1-RETSCH), and the theoretical specific surface area were monitored.

2.3. Mineralogical characteristics of zeolites

X - ray diffraction analysis was performed on characteristic samples of grinding products. X ray diffraction analysis was used to determine and monitor the phase composition of the samples. The samples were analyzed on an X-ray diffractometer of the "PHILIPS" brand, model PW-1710 with a curved graphite monochromator and a scintillation counter. The intensities of diffracted CuKα ray radiation (λ=1.54178Å) were measured at room temperature in the intervals of 0.02 °2θ and time from 1 and in the range from 4 to 65 °2θ. The X-ray tube was loaded with a voltage of 40 kV and a current of 30 mA, while the slots for directing the primary and diffracted beam 1° and 0.1 mm [14].

2.4. Modeling of artificial neural networks

In this research, models based on the Multi Layer

Perceptron were used, which in principle consist of three layers (input layer, hidden layer and output layer). The first estimation of the neuron number was obtained from a number of input and output neurons, the number of neurons in the hidden layer and number of weights (connections between layers) in the neural network. Number of neurons in a hidden layer depends on the complexity of the relationship between inputs and outputs. In this study, the number of hidden neurons in the ANN model varied from $n=4$ to 10. There were $x=3$ inputs, $y=15$ outputs, and $m=81-210$ wt coefficients (depending on n). Binary step was used in the activation function. The learning rate was 0.1.

The optimum number of hidden neurons was chosen upon minimizing the difference between predicted ANN values and desired outputs, using r^2 during testing as a performance indicator. The coefficient of determination (r^2) is compared below with

the values obtained by other researchers.

It is also the most commonly used and most flexible model of an artificial neural network of general purpose. The input values of this model were size class, grinding time and initial mass of the sample, while the output values were the content of the size class ($-5 + 0$) μm and the specific area. An artificial neural network with feed forward error backpropagation was used in the paper. The network "learns" using the Levenberg-Marquardt algorithm due to its high accuracy [12, 25].

3. Results and discussion

The increase in the time of micronizing grinding led to a change in the characteristics of zeolite and the manifestation of differences between unground and ground zeolite. The results of micronizing grinding are shown in Tables 2-5.

Table 2 Content of the size class ($-5 + 0$) μm of the sample ($-3.35 + 0$) mm, after micronizing grinding, starting masses (50, 100 and 200) g [14, 26]

50 g						
Time	20 s	45 s	75 s	120 s	300 s	900 s
Size class (μm)	-5 + 0	-5 + 0	-5 + 0	-5 + 0	-5 + 0	-5 + 0
W (%)	95.90	97.40	95.86	94.08	81.04	80.18
Spec. surface area (m^2/kg)	1056.02	1070.77	1056.65	1036.41	895.96	888.22
100 g						
Time	20 s	45 s	75 s	120 s	300 s	900 s
Size class (μm)	-5 + 0	-5 + 0	-5 + 0	-5 + 0	-5 + 0	-5 + 0
W (%)	90.98	94.15	95.83	94.31	82.11	64.99
Spec. surface area (m^2/kg)	1006.26	1039.44	1055.46	1038.20	908.23	723.16
200 g						
Time	20 s	45 s	75 s	120 s	300 s	900 s
Size class (μm)	-5 + 0	-5 + 0	-5 + 0	-5 + 0	-5 + 0	-5 + 0
W (%)	83.22	92.49	93.48	93.39	90.76	71.49
Spec. surface area (m^2/kg)	922.29	1020.16	1031.95	1031.64	1001.81	797.52

Table 3 Content of size class ($-5 + 0$) μm of sample ($-3.35 + 2.36$) mm, after micronizing grinding, starting masses (50, 100 and 200) g [14, 26]

50 g						
Time	20 s	45 s	75 s	120 s	300 s	900 s
Size class (μm)	-5 + 0	-5 + 0	-5 + 0	-5 + 0	-5 + 0	-5 + 0
W (%)	93.03	95.71	94.63	91.64	81.03	76.78
Spec. surface area (m^2/kg)	1027.67	1053.86	1042.69	1012.06	897.11	852.43
100 g						
Time	20 s	45 s	75 s	120 s	300 s	900 s
Size class (μm)	-5 + 0	-5 + 0	-5 + 0	-5 + 0	-5 + 0	-5 + 0
W (%)	89.92	94.83	95.34	94.78	86.63	74.49
Spec. surface area (m^2/kg)	996.46	1046.60	1050.40	1045.26	957.48	826.11
200 g						
Time	20 s	45 s	75 s	120 s	300 s	900 s
Size class (μm)	-5 + 0	-5 + 0	-5 + 0	-5 + 0	-5 + 0	-5 + 0
W (%)	77.75	90.72	93.01	95.33	92.97	76.82
Spec. surface area (m^2/kg)	864.01	1002.84	1027.77	1050.04	1024.66	849.60

Table 4 Content of size class (- 5 + 0) μm of sample (- 2.36 + 1.18) mm, after micronizing grinding, initial masses (50, 100 and 200) g [14, 26]

50 g						
Time	20 s	45 s	75 s	120 s	300 s	900 s
Size class (μm)	- 5 + 0	- 5 + 0	- 5 + 0	- 5 + 0	- 5 + 0	- 5 + 0
W (%)	94.12	96.53	96.37	93.04	85.80	79.29
Spec. surface area (m^2/kg)	1039.29	1062.18	1060.31	1026.50	946.92	878.86
100 g						
Time	20 s	45 s	75 s	120 s	300 s	900 s
Size class (μm)	- 5 + 0	- 5 + 0	- 5 + 0	- 5 + 0	- 5 + 0	- 5 + 0
W (%)	93.44	93.62	93.94	93.83	84.54	70.48
Spec. surface area (m^2/kg)	1029.96	1035.05	1037.55	1036.92	935.84	784.92
200 g						
Time	20 s	45 s	75 s	120 s	300 s	900 s
Size class (μm)	- 5 + 0	- 5 + 0	- 5 + 0	- 5 + 0	- 5 + 0	- 5 + 0
W (%)	81.80	92.42	95.61	95.69	93.65	75.18
Spec. surface area (m^2/kg)	906.09	1019.29	1054.08	1054.56	1032.70	833.96

Table 5 Content of size class (- 5 + 0) μm of sample (- 1.18 + 0) mm, after micronizing grinding, starting masses (50, 100 and 200) g [14, 26]

50 g						
Time	20 s	45 s	75 s	120 s	300 s	900 s
Size class (μm)	- 5 + 0	- 5 + 0	- 5 + 0	- 5 + 0	- 5 + 0	- 5 + 0
W (%)	96.28	96.15	92.75	91.72	86.98	82.84
Spec. surface area (m^2/kg)	1059.86	1058.75	1026.59	1015.20	961.18	919.22
100 g						
Time	20 s	45 s	75 s	120 s	300 s	900 s
Size class (μm)	- 5 + 0	- 5 + 0	- 5 + 0	- 5 + 0	- 5 + 0	- 5 + 0
W (%)	92.87	94.50	95.20	94.16	88.86	66.78
Spec. surface area (m^2/kg)	1025.54	1042.88	1049.27	1038.06	980.73	745.39
200 g						
Time	20 s	45 s	75 s	120 s	300 s	900 s
Size class (μm)	- 5 + 0	- 5 + 0	- 5 + 0	- 5 + 0	- 5 + 0	- 5 + 0
W (%)	82.41	92.72	94.37	93.87	90.60	76.17
Spec. surface area (m^2/kg)	912.77	1023.59	1040.74	1036.79	1001.55	844.26

As the time of micronized grinding increases, the content of the class (- 5 + 0) μm [12] and the specific surface area [12] increase until a certain grinding time, and after that it is assumed that agglomeration of samples occurs. For all samples, the optimal grinding time is between (45 and 75) seconds, during which time the sample is ground and the specific surface area is increased. At longer grinding times the specific surface area is reduced as the agglomeration process is assumed to take place. The content of the size class (- 5 + 0) μm increases to 95%, and then it reduces as grinding time increases. In order to determine whether agglomeration occurred, X-ray diffraction analysis was performed on a sample of class (- 3.35 + 0) mm with a starting mass of 50 g.

3.1. X-ray diffraction analysis

Figure 1 shows a comparative representation of the diffractogram of the unground sample and the sample with a starting weight of 50 g micronized (45, 120 and 900) seconds [14].

All samples were examined by X - ray diffraction on a polycrystalline sample. The mineral composition of the unground sample (Figure 1 a)) is as follows: HEU type minerals, quartz, feldspar, mica, and the most common is zeolite minerals, while quartz, feldspars and mica are significantly less represented. Of the feldspar, plagioclase is more predominantly represented than K-feldspar, and of the carbonate mineral, the presence of trace calcite was found. In the micronized sample for 45 seconds (Figure 1 b)), the content of zeolite minerals did

not decrease compared to the unground sample, and the effects of amorphization due to grinding were not seen [12]. In the sample shown in Figure 1 c), the content of zeolite minerals begins to decrease, and the effects of amorphization due to grinding are weak, while in the sample in Figure 1 d) the effects of amorphization due to grinding are very pronounced, and zeolite

minerals in the crystalline they are practically in shape [12], i.e. most of them are amorphized [8]. The authors [11, 12, 21, 22] also confirmed that agglomerations of zeolites occur after micronizing grinding. In order to see whether the obtained results can be tested and whether the results can be predicted, a neural network modeling was performed in the Matlab program.

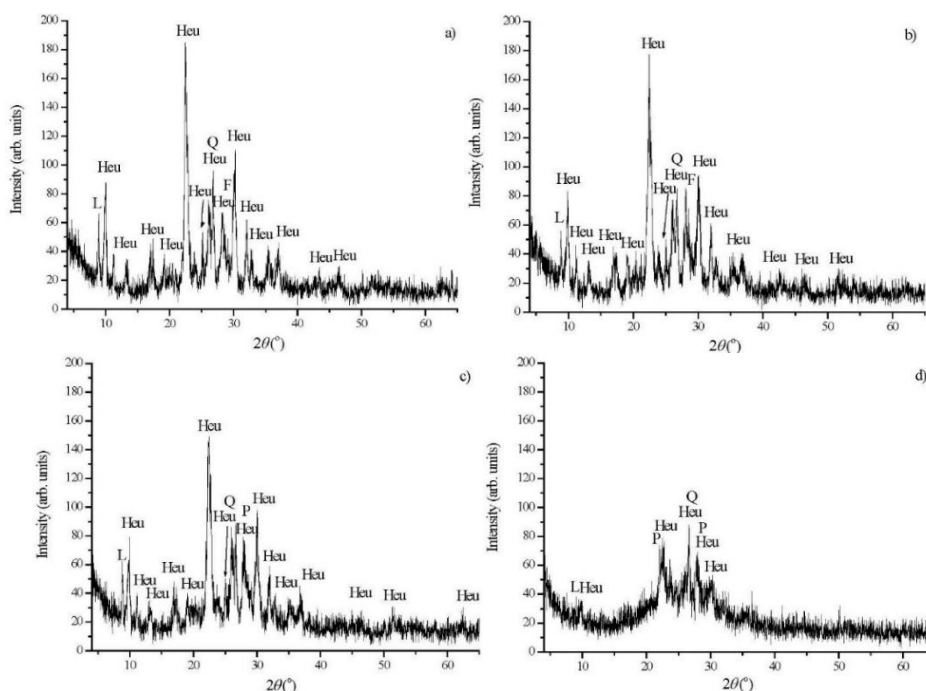


Figure 1 XRD analysis of unground sample (a) and sample with starting weight of (50 g) micronized: b) 45 sec; c) 120 sec; d) 900 sec [14]

3.2. Zeolite micronizing grinding modeling

The inputs of the models were size classes (-3.35 + 0 mm; -3.35 + 2.36 mm; -2.36 + 1.18 mm; -1.18 + 0 mm), grinding time (20 s, 45 s, 75 s, 120 s, 300 s, 900 s) and the initial mass of the sample (50 g, 100 g, 200 g), while the output values were content of the size class (- 5 + 0) μm and specific area. The results from Tables 2-5 were inserted into the Multi Layer Perceptron model and tested. The database used for modeling artificial neural networks in Matlab was divided into three sets: a network training set (70%), a validation set (15%) and a testing set (15%). A cross-validation data set was used to test network performance, while a data set used during the training was used as an indicator of the level of generalization and an indicator of the time when the network completed the training [12]. A set of test data

was used to examine the possibility of network generalization. Testing of the model showed that the network achieves good results, which is shown in Figure 2, having in mind a small set of input-output data. The accuracy of the results is confirmed by a very large coefficient R that ranges (0.989 - 0.997), which gives a satisfactory prediction accuracy. Comparing the obtained results with the results of other authors [8, 12], who for a much larger number of input-output data obtained that the value of the coefficient r^2 between experimental data and artificial neural network model data for size class content (- 5 + 0) μm is 0.811 for bentonite [8] and 0.936 for zeolite [12], it can be concluded that this model gave very good results, considering the much smaller the number of input-output data in relation to the authors [8, 12], and this statement is confirmed

by the moving coefficient R (0.989 - 0.997).

Figures 3 and 4 show a comparison of the calculated

values compared with the experimental data for the optimal artificial neural network.

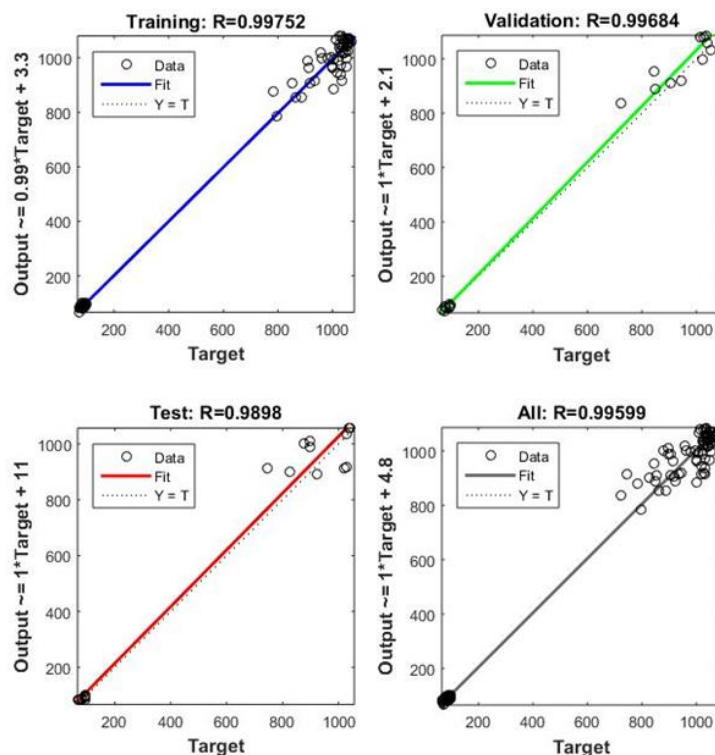


Figure 2 Experimentally obtained values of parameters and values obtained using the ANN model [26]

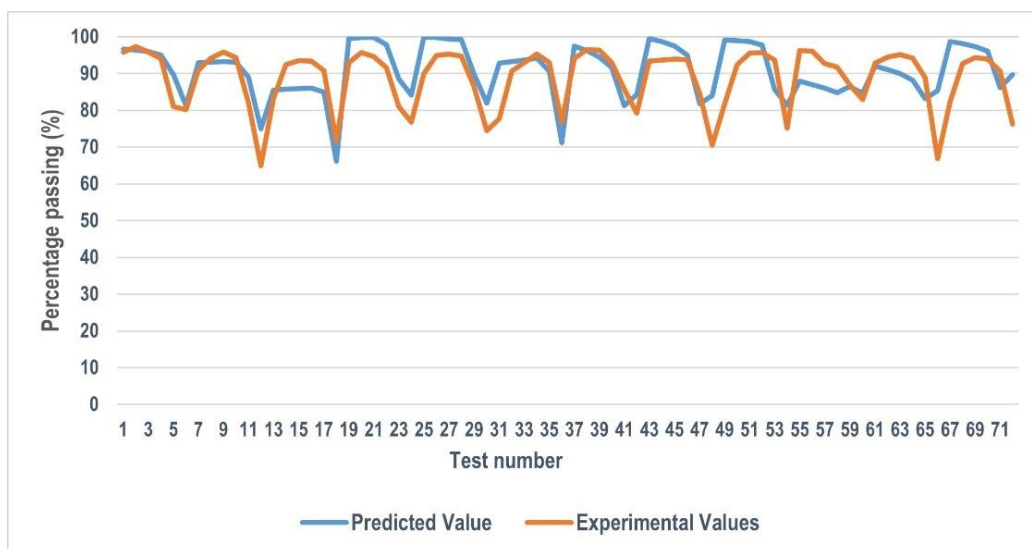


Figure 3 Comparative values of the content of the class $(- 5 + 0) \mu\text{m}$ obtained experimentally and using the ANN model [26]

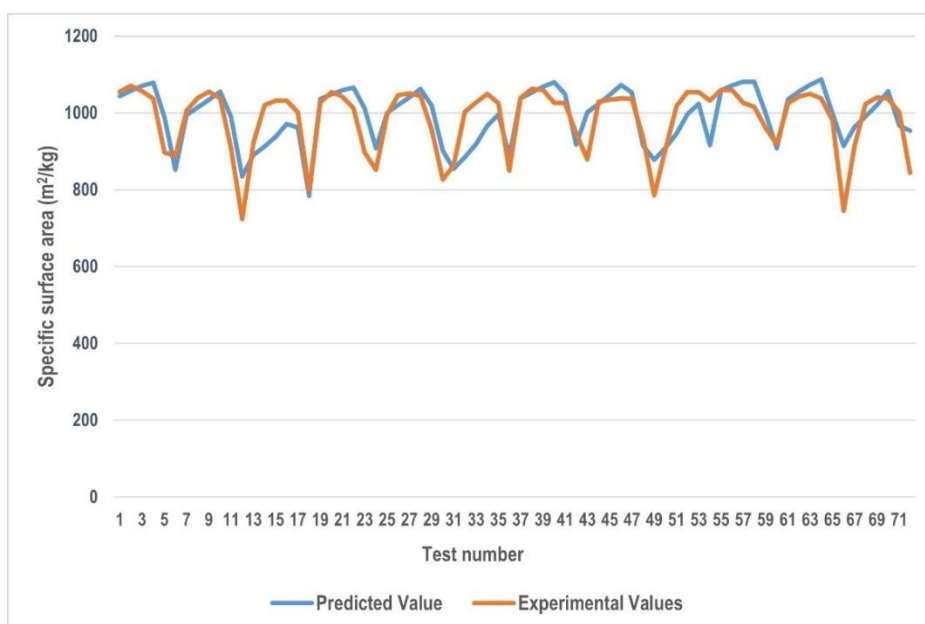


Figure 4 Comparative values of specific surface obtained experimentally and using the ANN model [26]

From diagrams 3 and 4 it can be seen that the modeling of the network is well done, the neural network has well captured the trend of change of curves obtained on the basis of experimental results. It was calculated that the mean error of the obtained model for the content of the size class $(- 5 + 0) \mu\text{m}$ is about 6%, and for a specific area about 4.5%, which is considered a very good prediction.

4. Conclusion

Micronizing grinding is a complex, long and complicated process, but the possibility of using neural networks as a tool for predicting results in such research facilitates and speeds up the work, and enables more accurate results. The study presents a comprehensive approach of artificial neural networks that can predict the content of the size class $(- 5 + 0) \mu\text{m}$ and the specific surface with great certainty. Neural networks are applied to this grinding process because neural networks rely less on an accurate physical model, and are mostly based on a statistic approach. Therefore, neural networks can be ideal for modeling this complex grinding process, which is the correlation coefficient and confirmed by its predictive accuracy that ranges (0.989 - 0.997). The mean error obtained for both models does not exceed 6%, which tells us that the model performed a very good prediction of the results.

Note

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OPTIMIZACIJA MIKRONIZACIJE MLEVENJA ZEOLITA KORIŠĆENJEM VEŠTAČKIH NEURONSKIH MREŽA

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Izvod

Mikronizirajuće mlevenje prirodnog zeolita, tipa klinoptilolit, ispitivano je u prstenastom mlinu. Cilj eksperimenta je bio da se odrede optimalni uslovi mlevenja za dobijanje praha sa odgovarajućim fizičko-hemijskim i mikrostrukturnim karakteristikama koji bi našao svoju potencijalnu primenu kao vezivo i jonski izmjenjivač u konstrukcionim kompozitima. Analiza određenih klasa krupnoće zeolita nakon mikronizacije izvršena je preko kinetike mlevenja. Istraživanja su vršena na prethodno pripremljenim uzorcima zeolita, na širim i užim klasama krupnoće (-3,35 + 0 mm; -3,35 + 2,36 mm; -2,36 + 1,18 mm; -1,18+0 mm) i različitim polaznim masama (50 g, 100 g, 200 g). Fino mlevenje je vršeno u različitim vremenskim intervalima (20 s, 45 s, 75 s, 120 s, 300 s, 900 s). Na proizvodima mlevenja izvršena je sitovna analiza, određen je sadržaj klase krupnoće (-5+0) μm i specifična površina ovih proizvoda. Na pojedinim proizvodima mlevenja izvršena je XRD analiza u cilju sagledavanja potencijalnih promena u samom materijalu-zeolitu. Veštačka neuronska mreža je razvijena na osnovu dobijenih rezultata, koja je nakon toga upoređena sa dobijenim eksperimentalnim rezultatima. Modeli veštačke neuronske mreže izvršili su zadovoljavajuću tačnost predviđanja (0,989 - 0,997) i mogu se smatrati preciznim i vrlo korisnim za predviđanje promenljivih odziva.

Ključne reči: zeolit, mikronizirajuće mlevenje, specifična površina, veštačke neuronske mreže.

NEW GENERATION OF ECOFRIENDLY REAGENTS BASED ON ORGANOSOLV LIGNIN NANOPARTICLES: ENVIRONMENTAL ASSESSMENT FOR AN AU FLOTATION CIRCUIT

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Abstract

Froth flotation is the leading process for the selective separation of minerals and the beneficiation of ores. The principle of the method depends on the different wettability properties of the minerals, specifically on the hydrophobicity of the surfaces, which is either inherent or imparted to the minerals through reagents. Despite their widespread and long-standing use, they are considered highly hazardous and toxic and their decomposition poses a potential risk in terms of safety, health, and environmental impact. A new viable alternative, that promotes sustainable development, is the production and utilization of organosolv lignin nanoparticles. This study examines the environmental benefits of producing of lignin nanoparticles from birch wood as and partially replacing xanthate collectors with lignin nanoparticles for the treatment of 1 tonne of mined ore, subjected to flotation. In order to quantify the environmental impact, a life cycle assessment (LCA) was conducted for an Au flotation circuit. The analysis demonstrated that the introduction of organosolv lignin into the flotation process along with the reduction of sodium isopropyl xanthate (SIPX) resulted in the decrease of the environmental footprint and in particular the reduction of climate change and fossil fuel depletion by 16.79% and 3.8%, respectively.

Key words: flotation, xanthate, lignin, life cycle assessment.

1. Introduction

1.1. The flotation process

In the mining industry, flotation is a physicochemical method of mineral beneficiation, through which selective concentration and separation from each other or from the gangue is achieved [1].

During the flotation process, the ground ore is placed in the flotation cell where it mixes with water to form a slurry. By introducing air into the cell, the hydrophobic surfaces of the particles adhere to the air bubbles. The density of the bubble-particle system is lower than that of the slurry, causing the rising of the particles to the surface of the flotation cell, and the formation of a froth collected by skimming. The removal of particles from the collected bubbles is achieved through water ionization. Upon the completion of flotation, the froth undergoes thickening and dewatering to minimize the moisture content. The hydrophilic

particles remaining in the flotation cell are classified as tailings [2, 3].

The presence of reagents can enhance the efficiency of the flotation process, allowing to obtain products of different desired compositions. One can distinguish reagents into collectors, frothers and modifiers. The selection of the appropriate reagent or the appropriate combination of reagents is a crucial step during the preparation of the flotation method and depends on the process assumption and the ore characteristics [4].

Collectors are organic chemical compounds that are characterized by amphiphilic properties, meaning they contain both hydrophobic and hydrophilic groups. The mechanism of a collector lies in imparting its hydrophobic characteristic to the mineral by adsorbing on its surface. The most frequently used collectors, especially in the flotation of nonferrous minerals are xanthates. Their choice is justified by their high

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efficiency (high selectivity of minerals) and their economic advantage (relatively low cost) [5].

However, the use of xanthates is approached with more concern and it's subject to increasing criticism due to their toxicity. Xanthates can be released into the environment in different ways from manufacturing (e.g. residue generation), transport (e.g. accidental spillage), storage, application and waste disposal (e.g. spillage from litter) [6]. During the hydrolyzation of non-aqueous solutions and flotation pulps, they degrade easily forming toxic substances such as carbon disulfide (CS_2), carbonyl sulphide (COS), alcohol (R-OH), carbonic anion ($2CO_3^{2-}$) and hydrogen sulphide (H_2S). These compounds pose a serious threat for the environment and humans' safety [7, 8].

1.2. Lignin

Lignocellulosic biomass is the most common organic polymer, accounting for about 1.5 trillion tonnes of total annual biomass production. Its main sources are forest residues and the pulp industry, representing the largest renewable organic source and an inexhaustible supply of raw materials. It is composed of three main polymers: cellulose, hemicellulose, and lignin, which provide lignocellulose with a complex and heterogeneous structure. There is a great variation of the composition and concentration of each polymer according to the type of lignocellulosic biomass. The function of lignin represents 10-25% of the biomass and its chemical structure varies significantly depending on its source [9, 10]. It is a heterogeneous, aromatic, long-chain polymer made up of propanophenol units, mostly connected by ether linkages. Lignin's covalent association with hemicellulose and cellulose molecules hinders the penetration of enzymes that hydrolyse polysaccharides and the extraction of carbohydrates in aqueous solvents, resulting in strong hydrophobic behaviour. Despite containing hydrophilic groups, its three-dimensional structure imparts hydrophobicity and insolubility in water at acidic or neutral pH, though it can dissolve in various organic solvents like ethanol, acetone, and chloroform, as well as in alkaline solutions at high temperatures of 150-180 °C [11].

The three most common types of lignin that can be produced by using different treatment methods are sulfonic lignin, Kraft lignin, and organosolv lignin. The organosolv pre-treatment is particularly effective for biomass delignification, producing clean streams of cellulose, hemicellulose, and lignin. Organosolv lignin

(OL) is currently gaining popularity due to its high quality, low ash content, and lack of sulphur compared to Kraft and sulfonated lignin [12].

This study introduces the use of modified flotation reagents with the addition of OL, an economically and ecologically beneficial approach, which promotes European policy and offers a viable solution for the production of renewable, low carbon footprint and economically sustainable collectors. Developing a reagent for the flotation process that uses biodegradable and eco-friendly organosolv lignin as the primary component could decrease the reliance on xanthates and reduce the associated negative impacts, offering a valuable alternative.

2. Experimental

2.1. Purpose and scope definition

Standardized by ISO 14040:2006 and ISO 14044:2006 and guided by the International Life Cycle Data (ILCD) Handbook, life cycle assessment (LCA) evaluates the inputs, outputs of a product or system and the environmental impacts associated with its life cycle. As a methodological framework, it consists of four main phases:

- 1) goal and scope definition,
- 2) inventory analysis,
- 3) impact assessment and
- 4) interpretation [13].

In the current study, LCA is performed in order to quantify and estimate the environmental impact for the evaluation of the replacement of isopropyl xanthate (SIPX) with a new organosolv lignin-based collector in the flotation process. The scope of the study focuses on examining the environmental advantages of partially replacing xanthate reagents with organosolv lignin nanoparticles (OLN).

Definition of functional unit

The functional unit is defined as 1 kilogram of sulphide ore which is processed to obtain a sphalerite concentrate. The following feed treatment consists mainly of pyrite, arsenopyrite, and the waste from the previous process. The treatment of the ores results in the recovery of pyrite/arsenopyrite concentrate from which gold is extracted as the final product.

System boundaries

For the quantification and evaluation of environmental impacts, a gate-to-gate LCA is conducted

and the system boundaries are defined. For the production of the reagent the pretreatment of birch wood biomass to produce organosolv lignin and the production of lignin organosolv nanoparticles are included in the methods boundaries.

Two scenarios were applied for the flotation process. In the base case scenario (BSC), isopropyl xanthate is selected while in the alternative scenario 1 (S1), a mixture of 50% isopropyl xanthate and 50% lignin organosolv reagent is chosen as the collector reagent. The system boundaries for the flotation process include the production of xanthate and lignin organosolv nanoparticles, the transportation of xanthate, the use of xanthate collector in BSC, and the use of lignin organosolv and xanthate collector in S1 for the gold recovery.

Assumptions and limitations

In the LCA method, all materials and energy required during the life cycle of the product or system should be included. However, while conducting the life-cycle inventory and impact assessment it is advised to make assumptions in case of lack of time, resources, and data.

In the current study, regarding transportation, it is assumed that xanthate is purchased and transported from China while the origin country of lignocellulosic biomass is Sweden. The data concerning the components of the flotation system as well as the synthesis processes of the organosolv lignin nanoparticles, such as the quantities of the materials and energy, are confidential; therefore, they are not published in this study.

2.2. Life cycle inventory analysis

In this section, LCI involves the data collection for the production of the OL reagent and the inputs and outputs of the flotation system. The necessary data are acquired from the laboratory process [14].

For the production of organosolv lignin, 8.57 kg of birch wood biomass were added in 85.7 L of solvent containing 50% v/v ethanol and water. The solution was treated at 180 °C for 2h by using electricity, without the presence of acid catalyst. At the end of the treatment, two fractions were collected: the cellulose solution and the hemicellulose and lignin solution. Then, lignin was recovered from the pretreated liquor of hemicellulose and lignin by evaporation. After lignin removal, the ethanol solution containing the solubilized hemicellulose

is fully recovered and recycled. The fraction containing the cellulose is washed with water.

The inputs and outputs of the system are shown in Table 1 and Figure 1.

Table 1 Inputs and outputs of OL pretreatment

	Flow	Quantity	Unit
Inputs	Utreated birch wood biomass	8.57	kg
	Ethanol	42.85	L
	Water	42.85	L
	Electricity	259.056	MJ
Outputs	Pretreated birch wood biomass	5.23	kg
	Raw organosolv lignin (OL)	1.000	kg
	Hemicellulose fraction	0.242	kg
	Recovered liquid	85.700	L

The utilisation of organosolv lignin in the flotation process requires the treatment of the lignin in order to obtain the desirable nanoparticles size. The nanoparticles are formed through solvent exchange method. The lignin is dissolved in an ethanol-to-water solution and mixed for 8 hours. Homogenisation is carried out at 750 bars with a pressure homogeniser. For the synthesis of nanoparticles, the solution is diluted with deionised water in a ratio of 1:6 yielding the particles in the form of dry powder. The collection of the particles was accomplished through the lyophilization process.

The inputs and outputs of the gold flotation system for the base case scenario are shown in Table 2 In scenario 1, 50% isopropyl xanthate and 50% organosolv lignin reagent is used as the collector reagent. The inputs and outputs of the gold flotation system for scenario 1 are shown in Table 3.

2.3. Life cycle inventory analysis

In the LCIA phase, the LCI results are associated to environmental impact categories and indicators. The selected impact categories are obtained from ReCiPe 2016, a more extended and updated version of ReCiPe 2008, which was developed by the Royal Netherlands Institute for Public Health and the Environment (RIVM), Radboud University in the Netherlands, the Institute for Environmental Sciences (CML) at Leiden University in the Netherlands, and PreSustainability BV. Endpoint characterisation factors

are associated to the areas of protection and obtained from midpoint characterisation factors using a consistent mid-to-endpoint factor for each impact category. The midpoint environmental impact assessment method contains 18 impact categories, from which 11 are examined in this study. The impact categories that will be considered are:

- Climate change,
- Fossil depletion,
- Freshwater ecotoxicity,
- Freshwater eutrophication,
- Human toxicity, cancer,
- Ionizing radiation,
- Land use,
- Marine ecotoxicity,
- Photochemical ozone formation, human health,
- Stratospheric Ozone Depletion,
- Terrestrial Acidification.

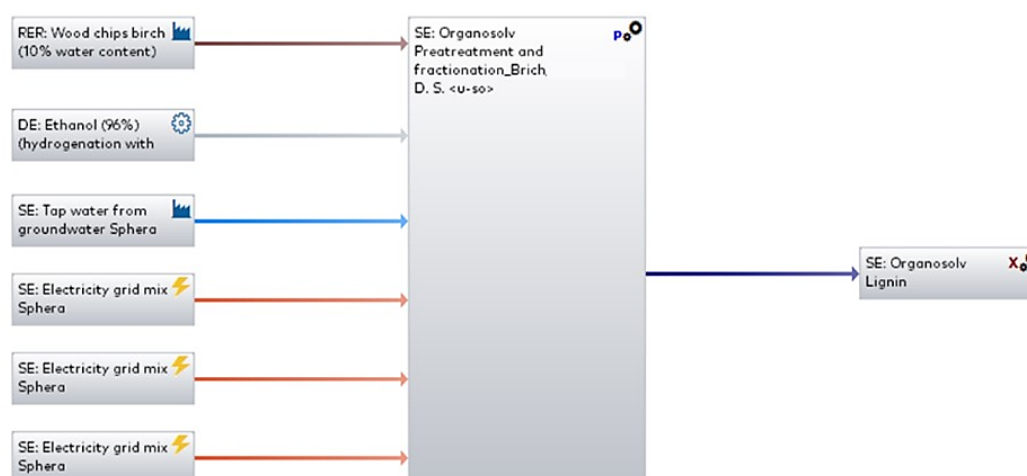


Figure 1 Sphera Model LCA FE software for the pretreatment of birch wood

Table 2 Inputs and outputs of Au flotation system (Base case)

Au flotation system	Inputs	Pyrite/ Arsenopyrite + Tailings
		Collector (SIPX)
		Water
		Electricity
		Xanthates transport distance
Outputs	Pyrite/ Arsenopyrite concentration	
	Waste for disposal	

Table 3 Inputs and outputs of Au flotation system (Scenario 1)

Au flotation system	Inputs	Pyrite/ Arsenopyrite + Tailings
		Collector (SIPX)
		OL nanoparticles reagent
		Water
		Electricity
		Xanthate transport distance
	OL nanoparticles reagents distance	
Outputs	Pyrite/ Arsenopyrite	
	Waste for disposal	

In order to reflect varying views on time preference, uncertainty or local preference, three different perspectives were created (hierarchical, individualist and egalitarian). The hierarchical perspective is considered the most balanced type as it attains a middle ground between future and present impacts, between risks and benefits, and between local and global concerns. Nevertheless, the hierarchical perspective is applied for the purpose of this study.

3. Results

This section presents and evaluates the results of the life cycle analysis for the investigated system, as well as for all the examined scenarios. Tables 4 and 5 demonstrate the quantified results of BCS and S1 by Sphera Software for each impact category.

From the outcomes of the two evaluated scenarios presented in the Tables 4 and 5 and the Figures 2, 3, and 4 it is shown that the introduction of organosolv lignin in the production of collecting reagents contributes to the reduction of the environmental footprint of Au

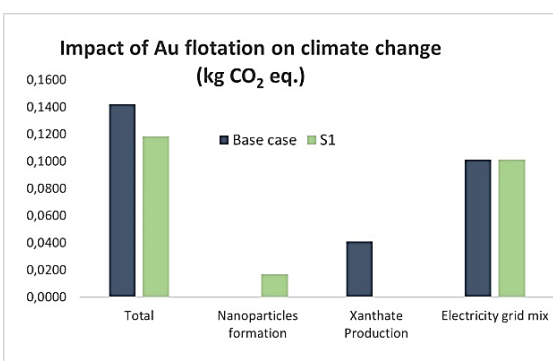
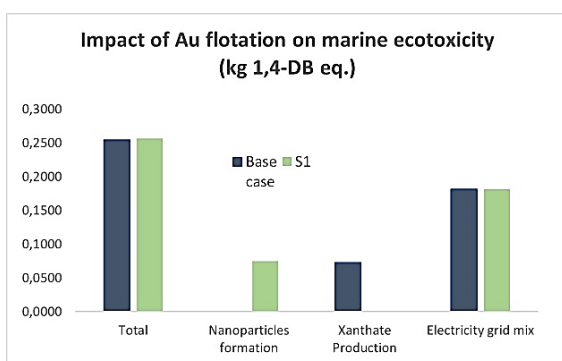
flotation. In more detail, from the comparison of the environmental impact values of the base case and scenario 1 circuits, it is estimated that the replacement of xanthate with organosolv lignin nanoparticles reagent shows more environmentally friendly values in all impact categories.

Table 4 Environmental impact values of the Au flotation circuit (base case)

Impact categories	Total	Xanthate Production	Transport (rail)	Pyrite/APy Concentrate	Electricity grid mix	Py/APy Ore
Climate change [kg CO ₂ eq.]	0.1423	0.0409	0.0000	1.41E-05	0.1014	0.0000
Fossil depletion [kg oil eq.]	0.1811	0.0409	0.0713	0.000000	0.0296	0.0305
Freshwater ecotoxicity [kg 1,4-DB eq.]	0.0261	0.0261	0.0000	0.000000	9.60E-06	0.0000
Human toxicity, cancer [kg 1,4-DB eq.]	0.0010	0.0005	0.0000	0.000000	0.0005	0.0000
Ionizing radiation [kBq Co-60 eq.]	0.0910	0.0894	0.0000	0.000000	0.0017	0.0000
Marine ecotoxicity [kg 1,4-DB eq.]	0.2539	0.0725	0.0000	0.000000	0.1814	0.0000

Table 5 Environmental impact values of the Au flotation circuit (Scenario 1)

Impact categories	Total	Nanoparticles formation	Xanthate Production	Transport (rail)	Pyrite/APy Concentrate	Electric grid mix	Py/APy Ore
Climate change [kg CO ₂ eq.]	0.1184	1.03E-04	0.0169	0.0000	1.41E-05	0.1014	0.0000
Fossil depletion [kg oil eq.]	0.1742	9.38E-05	0.0340	0.0713	0.000000	0.0296	0.0305
Freshwater ecotoxicity [kg 1,4-DB eq.]	1.81E-05	3.04E-08	8.50E-06	0.0000	0.000000	9.60E-06	0.0000
Human toxicity, cancer [kg 1,4-DB eq.]	9.15E-04	1.58E-04	0.0003	0.0000	0.000000	0.0005	0.0000
Ionizing radiation [kBq Co-60 eq.]	0.0746	3.32E-05	0.0729	0.0000	0.000000	0.0017	0.0000
Marine ecotoxicity [kg 1,4-DB eq.]	0.2566	0.0749	0.0004	0.0000	0.000000	0.1814	0.0000



Figures 2 and 3 Results of Au flotation measurements on climate change and marine ecotoxicity

A significant improvement is observed in the freshwater ecotoxicity category which is justified by the reduction of the highly toxic xanthate in the aquatic ecosystems. An important difference is also observed in the climate change category with a reduction of 16.79% which is explained by the production of less xanthate compared to the base case scenario. In general, xanthate is associated with greenhouse gas emissions, and therefore the increase in the emitted kg of carbon dioxide (CO₂), justifying the reduction of the value.

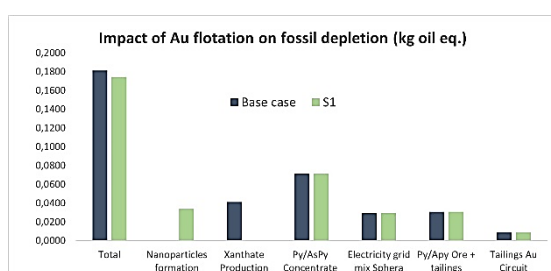


Figure 4 Results of Au flotation measurements on fossil fuel depletion

The value of fossil fuel depletion category is decreased by 3.8% which could contribute to a significant environmental benefit, considering the potential impact on the values on industrial scale processes. The categories of ionizing radiation and destruction of stratospheric ozone show considerably lower values, 18.08% and 24.5% respectively, while the rest of the impact categories show a reduction range from 1% to around 10%. An increase of 1% is detected in the category of marine ecotoxicity which is attributed to the formation of lignin nanoparticles.

4. Discussion

This study aimed to conduct a comprehensive environmental assessment of the use of organosolv lignin reagent in a flotation circuit. The analysis showed that organosolv lignin collectors mixed with xanthate (50% w/w) had a significant improvement in the environmental impact of gold flotation compared to xanthate collectors. In addition to its environmental benefit, lignin can contribute to the support and independence of the European reagents market. With China owning the largest share of production and consumption, the xanthates market size is expected to reach USD 130.5 million by 2027, at a compound annual growth rate (CAGR) of 8.7% during the analysis period, 2020-2027. As a low-cost organic material with

almost abundant sources and an increasing global production (expected to reach over \$913.1 million by the year 2025) lignin can efficiently replace or limit the xanthate use in the flotation process [15].

Despite its performance in beneficiation methods and its advantages over conventional reagents, the use of lignin-based collectors is only implemented on a laboratory scale. The lack of technical maturity and commercialised solutions poses challenges on the implementation of lignin-based collectors on the mining industry. Regarding the scale-up, many factors affect the process, including the feed, the sizes and design of the industrial cells, the circuit layouts, and the operating conditions of the plant. Experimental data have shown that the approximate flotation rates of ore concentrate recovery in industrial plants are lower than those calculated in laboratory tests. However, the different flotation conditions applied by each plant, as well as parameters such as the type of machines, the operator skills and the feed samples affect the scale-up, making it difficult to adopt a common method of estimating its factors [16].

For the scale-up process of the study, the most efficient method has been proven the estimation of the results by engineering (process simulation, full-scale plant modelling in a virtual environment, calculation of mechanical processes using mass and energy balances) and stoichiometric analysis. A combination of laboratory-scale data and kinetic equations can provide a better approach to industrial results in order to determine the environmental impact [17].

In order to validate these frameworks and to analyse the performance and reliability of the scale-up methods, the laboratory and industrial production processes were investigated. The main idea of all frameworks was to design a scale-up system for the new technology based on similar existing industrial processes. The stages of the scale-up include the simulation of the laboratory and industrial processes, the quantitative description of the new material production and the analysis of the ratios of the scale-up processes [17, 18].

5. Conclusions

This study highlights and evaluates the environmental impacts arising from the flotation process using xanthate reagents, while also examines the environmental benefits of adding organosolv lignin nanoparticles in flotation for the partial replacement of xanthate (50%). The analysis showed that for the

production of organosolv lignin, the use of ethanol was the most critical factor contributing to the increase in the environmental impact values, while in the flotation process the main impacts were related to the consumption of electricity and the use of xanthate. In total, the partial replacement of SIPX with OLN resulted in the reduction of 9-10% in the environmental impact of Au flotation. The addition of OLN in the collector mixture and the parallel reduction of SIPX could contribute to the transition to environmentally friendly reagents and therefore to the reduction of the environmental footprint of metallurgical processes.

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NOVA GENERACIJA EKOLOŠKIH REAGENSA NA BAZI NANOČESTICA ORGANOSOLV LIGNINA: PROCENA UTICAJA POSTROJENJA ZA FLOTACIJU ZLATA NA ŽIVOTNU SREDINU

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Izvod

Flotacijska koncentracija je vodeći proces za selektivnu separaciju minerala i obogaćivanje ruda. Princip metode zavisi od različitih osobina kvašenja minerala, tačnije od hidrofobnosti površina koje su ili prirodno hidrofobne ili naknadno postaju dejstvom reagensa. Iako su reagensi široko rasprostranjeni i dugo se koriste, smatraju se veoma opasnim i toksičnim, a njihova razgradnja predstavlja potencijalni rizik po bezbednost, zdravlje i uticaj na životnu sredinu. Nova održiva alternativa koja promoviše održivi razvoj je proizvodnja i upotreba nanočestica organosolv lignina. Ova studija ispituje ekološke prednosti proizvodnje nanočestica lignina od brezovog drveta kao i delimične zamene kolektora ksantata nanočesticama lignina za preradu jedne tone iskopane rude, podvrgnute flotaciji. Kako bi se kvantifikovao uticaj na životnu sredinu, sprovedena je procena životnog ciklusa (LCA) postrojenja za flotaciju zlata. Analiza je pokazala da uvođenje organosolv lignina u flotacijski proces, zajedno sa smanjenjem natrijum izopropil ksantata (SIPX), rezultira smanjenjem uticaja na životnu sredinu, a posebno smanjenjem klimatskih promena i iscrpljivanja fosilnih goriva za 16,79% i 3,8%, respektivno.

Ključne reči: flotacija, ksantat, lignin, procena životnog ciklusa.

ANALYSIS OF CRACK RESPONSE ON STRUCTURES DUE TO BLASTING AND NON-BLASTING FACTORS

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Abstract

Seismic waves caused by blasting activities can be a source of damage to structures. The most common damage is the appearance of cracks or the widening of existing cracks. Structures are also affected by environmental factors. Depending on the conditions, temperature and humidity can cause a stronger reaction in the cracks than blasting. However, the effects of non-blasting factors last much longer than those of blasting, so the load gradually increases, allowing for an even and timely distribution of stress around the crack tip. On the other hand, blasting factors act over a short period of time, resulting in a rapid increase in the stress intensity factor at the crack tip and a faster release of stress energy. The FEM (finite element method) analysis of these impacts was conducted on a model in the ABAQUS CAE software. The results of the analysis show that the influence of blasting factors is significantly higher compared to the influence of non-blasting (environmental) factors. The strain energy and the stress intensity factor per unit time are much higher under the influence of blasting factors. The strain energy is 9.58×10^{10} times higher, and the stress intensity factor at the crack tip is 309583 times higher due to the dynamic load, observed over a period of 0.033 seconds.

Key words: seismic waves, blasting, FEM method, ABAQUS CAE, crack, environmental factors.

1. Introduction

Primary blasting is one of the several fundamental technological phases in the process of surface and underground excavation of solid rock masses, mineral raw materials, or overburden. It is conducted with the largest diameters of boreholes, the greatest quantity of explosives per blast, and the largest volume of material prepared by a single blast for further technological processing [1].

This technological operation is accompanied by undesirable and unavoidable effects, such as seismic waves that people perceive as tremors or ground vibrations. Ground vibrations can have significant intensity and may cause damage to nearby structures. As the seismic wave passes through the foundation soil of a structure, it causes oscillation of the structure itself, which can lead to the occurrence of damage in the form of new structural cracks (deep cracks in walls, supporting columns, etc.), facade cracks, or the widening of existing cracks [2].

Damage to structures may also exist prior to the passage of seismic waves generated by blasting. Pre-existing structural damage can result from a variety of factors, such as natural seismic waves (earthquakes), soil subsidence or uplift, landslides, the impact of wind, water, sun, frost, etc. [3, 13, 14].

Numerous studies highlight the significant impact of daily temperature changes, humidity variations, soil settlement, and everyday human activities on structural damage. They indicate that, in some cases, the impact of blasting is considerably smaller than the aforementioned influences. However, regardless of how small the impact of blasting may be, it should not be ignored [3].

The impact of each factor on structural cracks is generally observed through the reactions of the cracks themselves, particularly their widening. However, when comparing the duration of blasting and non-blasting factors, a significant difference can be noted. The duration of blasting factors is on the order of milliseconds (ms), whereas the duration of non-blasting

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factors can span several hours or even days.

The impact of blasting, as a transient dynamic load, although it affects structures for a short period of time (ms), induces complex stresses within them that are significantly greater than those from loads acting over longer periods [4]. Previous studies have focused on monitoring crack responses to environmental influences over durations of 37 hours and to the passage of seismic waves [4]. Therefore, this study aimed to confirm, based on longer durations (72 hours) and more extensive measurements across multiple cracks, that dynamic stress resulting from ground vibrations indeed causes higher stresses at the crack tip.

According to references [3, 4-10], the crack response in terms of its widening due to blasting can be much smaller compared to the influence of other factors. However, the stress intensity at the crack tip is significantly higher with blasting-induced vibrations because these are dynamic stresses. Specifically, research results from [4] indicate that due to dynamic loading, the equivalent crack response is 126 times greater compared to the influence of other (static) stresses.

Results from the literature provide the basis and motivation to continue further detailed research on this topic. Flowchart of the research methodology is shown in the Figure 1.

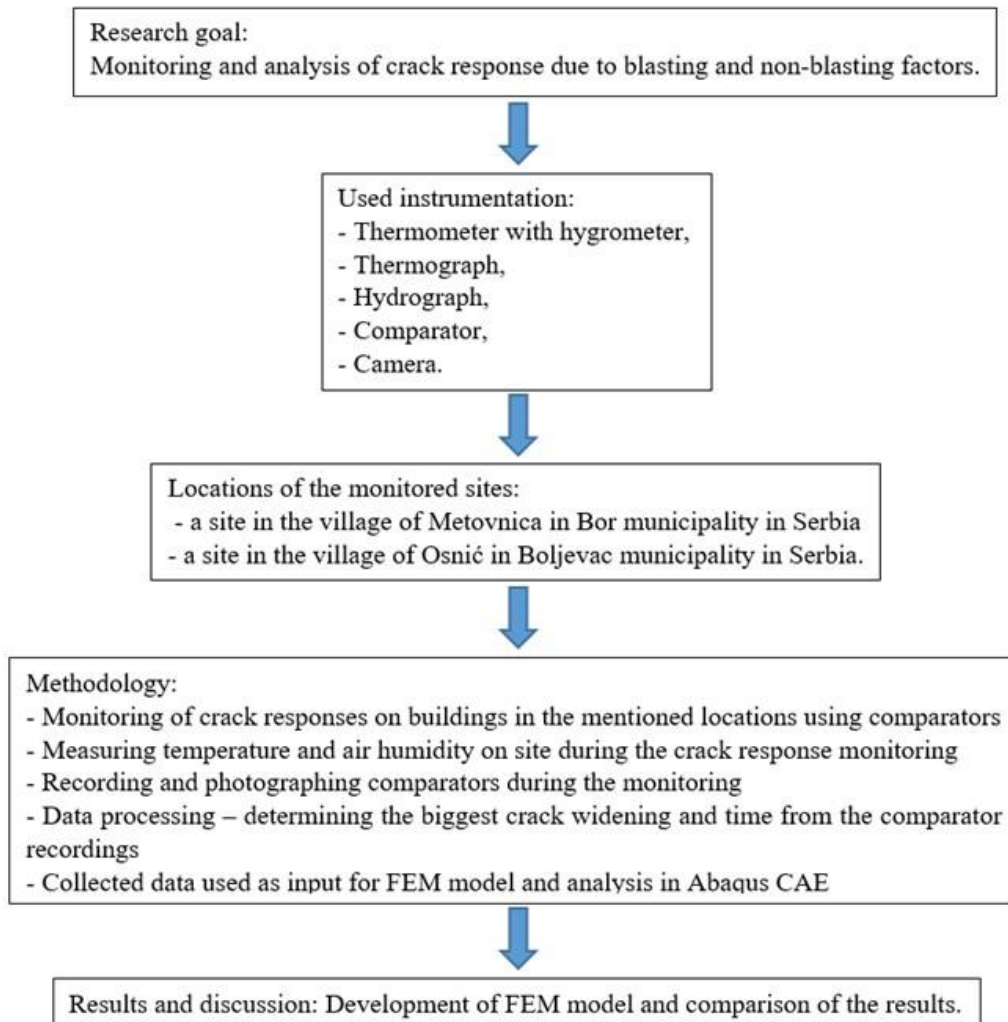


Figure 1 Methodology flowchart

2. Materials and Methods

To monitor the responses of structural cracks on residential buildings exposed to environmental influences and seismic waves resulting from blasting, the following equipment was used:

HACCURY DYWSJ thermometer with hygrometer capable of measuring temperature and relative humidity of the air (temp. range -30 to +50 °C, RH range 0-100 %, temp. tolerance +/-1 °C, moisture tolerance ±5%), Veb. Feingeratebau thermograph and hydrograph (temp. range -35 °C to +45 °C, RH range 0-100 % and tolerance ±3%), comparator manufactured by Soil Test Inc., Evanston, IL, USA. This comparator has a measurement range up to 25 mm, with the scale graduated in 0.01 mm increments. The monitored influential parameters include temperature (°C), relative humidity (%), and crack reaction (mm).

For the purposes of this study, research was conducted at two locations. The first measurements were carried out at a site in the village of Metovnica in Bor region in Serbia, where the crack response during blasting was monitored during the construction phase of two parallel declines for exploratory work in the copper and gold deposit "Čukaru Peki" (Figure 2).

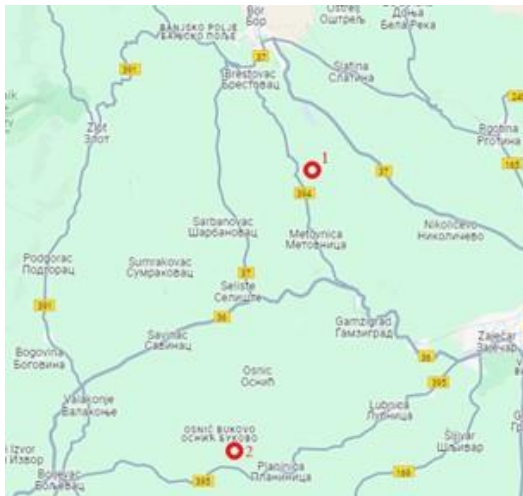


Figure 2 Locations of the monitored sites

The second set of measurements was conducted at an old family house in the village of Osnić in Boljevac municipality in Serbia (Figure 2), where the responses of three cracks to environmental influences were monitored.

The monitoring of crack responses to seismic waves

caused by blasting was conducted on an older building near the current mining operations. For measurement purposes, a comparator was used, placed on a structural crack between stone blocks of the building (Figure 3). The cause of the crack formation was not determined; it is possible that the crack occurred due to the age of the building and prolonged exposure to natural factors, primarily soil settlement.



Figure 3 Comparator on the object at Metovnica site

Photographs and video recordings were used to capture the crack response in terms of the movement of the comparator's pointer. Monitoring of the crack response on this building was conducted in two series of blasts, resulting in two recordings that were further analyzed. Since seismic waves caused by blasting induce short-term movements, recording the comparator itself provided the best method for tracking the crack response.

At the building in the village of Osnić, the monitoring of crack response to environmental influences was conducted. Due to the age of the building and the variety of materials used in its construction, the structure has experienced multiple damages manifested as structural cracks.

The cracks are most likely a result of land sliding (the house is located on a slope), soil settlement, and uplift due to inadequate rainwater drainage systems. However, the exact causes of these damages have not been precisely determined. Cracks are present on each side of the building, so measurements were conducted on three cracks: one on the shaded side, one on the sunny side, and one on the partially sunny side of the house.

Before the measurements began, a thermograph and hydrograph were placed near the crack to record temperature and relative humidity readings (Figure 4). Additionally, a thermometer with a hygrometer was placed next to the wall of the building.



Figure 4 Thermograph and hydrograph positioned near the cracked wall

The first measurement was conducted on the shaded side of the house, where the crack runs from bottom to top, possibly caused by ground uplift or sliding

(Figure 5a). A comparator was mounted directly on the crack, and before measurements commenced, the comparator was zeroed and photographed (Figure 5b).

Measurements were taken every 2 hours over a period of three days (72 hours for one crack). Preparation for measurement, reading values, as well as the assembly and disassembly of the comparator, were identical for each reading series.

The first reading was conducted on the shaded side. After completing the readings, the position of the comparator pointer was photographed, followed by disassembly and relocation of the comparator to the next crack.

The next series of readings were conducted on the sunny side of the house (Figure 6).

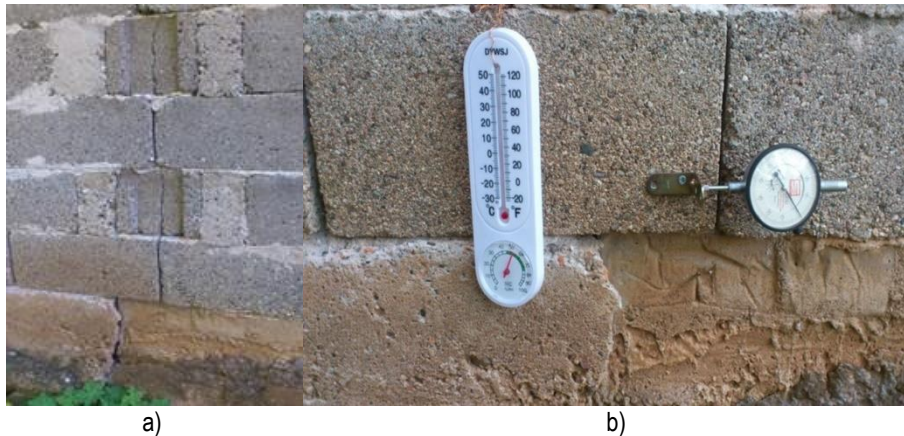


Figure 5 Crack on the shaded side (a) with the thermometer and comparator at the start of monitoring (b)

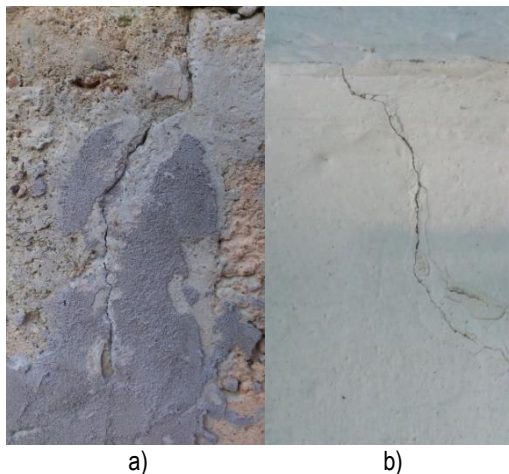


Figure 6 Crack on the sunny side, outside (a) and inside (b)

The last reading was taken on the partially sunny side of the house (Figure 7).

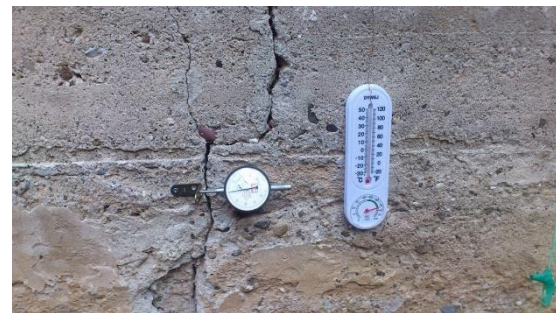


Figure 7 Crack on the partially sunny side with thermometer and comparator

3. Results of the research and discussion

Two recordings were analyzed showing the crack response to the seismic waves caused by blasting, as recorded by the comparator. The recordings were divided into frames using media player software, specifically "KMPlayer." The frame rate (fps - frames per second) of the recordings was 30 fps, meaning there were 30 frames per second. With this in mind, the duration of one frame can be determined using the formula (1):

$$30 \text{ fps} \rightarrow \frac{1}{30} = \frac{\text{second}}{\text{frame}} = 0.0333 \left[\frac{\text{s}}{\text{frame}} \right] \quad (1)$$

Out of the total number of frames (considering both recordings), 160 frames were selected for analysis (60 frames for the first recording and 100 frames for the second recording), from which the displacement values of the comparator pointer were read. This method determined the displacement value of the comparator pointer per frame. The obtained data were further processed in Microsoft Excel 2010 (Figure 7).

The decreasing values of the comparator displacement represent crack widening, while increasing values indicate crack closure or contraction. It was found that for Recording 1, the largest crack widening reaction was 0.042 mm (ranging between -0.002 mm and 0.04 mm) over a time period of 0.033 s (from 0.693 s to 0.726 s), whereas for Recording 2, the largest crack widening reaction was 0.012 mm (ranging between -0.01 mm and 0.002 mm) over a time period of 0.033 s (from 1.551 s to 1.584 s).

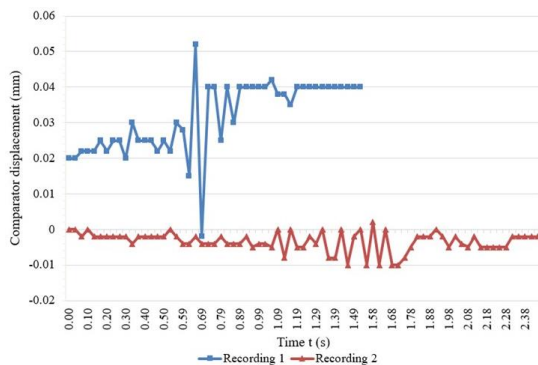


Figure 8 Crack response due to blast vibrations

After recording all parameters and crack responses on the building in the village of Osnić, the obtained data

were further processed similarly to the previous case. Through data processing, it was determined that the largest crack reaction occurred on the sunny side (Crack 2), with a widening of 0.210 mm (ranging between -0.1 mm and 0.11 mm) over a period of 14 hours (from 16:00 on Day 2 to 06:00 on Day 3). On the partially sunny side (Crack 3), the widening was 0.048 mm (ranging between -0.002 mm and 0.046 mm) over 16 hours (from 16:00 on Day 1 to 08:00 on Day 2), and on the shaded side (Crack 1), it was 0.010 mm (ranging between -0.028 mm and -0.018 mm) over 36 hours (from 16:00 on Day 1 to 18:00 on Day 3) (Figures 9 – 11).

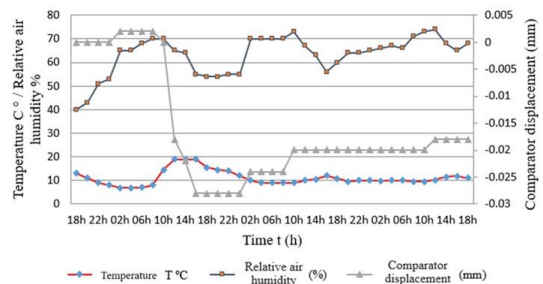


Figure 9 Graphical representation of changes in temperature, relative humidity, and crack 1 response

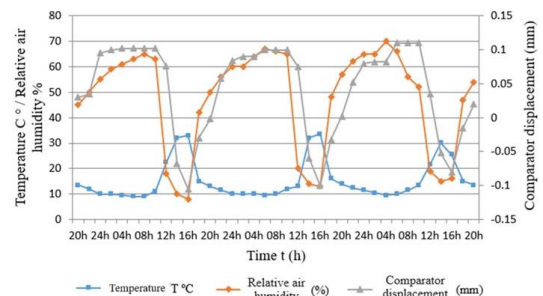


Figure 10 Graphical representation of changes in temperature, relative humidity, and crack 2 response

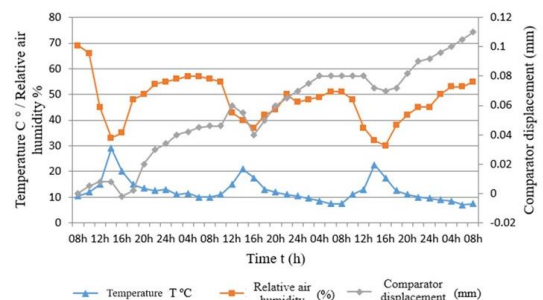
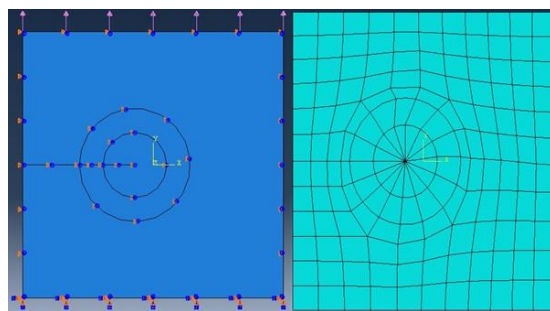


Figure 11 Graphical representation of changes in temperature, relative humidity, and crack 3 response

Obtained data from comparator displacement and duration of crack response was used as input data for FEM model and further analysis. FEM is a numerical method used for solving engineering and mathematical physics problems. Analytical solutions to these problems require solving boundary value partial differential equations. FEM utilizes variation methods to obtain exact or approximate solutions. The study or analysis conducted using FEM is often referred to as Finite Element Analysis (FEA). The finite element method (FEM) is commonly used in evaluating blast-induced ground vibrations, either individually or coupled with other methods. The numerical approach by FEM allows monitoring, in time and space, the seismic waves. This facilitates the evaluation of the rock mass response to the induced dynamic efforts. [11, 12].

Abaqus CAE (Complete Abaqus Environment – Computer Aided Engineering) is equipped for FEM analysis and is used for modeling and analyzing mechanical components and assemblies, as well as for displaying the results of FEM analysis. For this study, the academic version of the software, SIMULIA Abaqus Student Edition 2018, was used. However, the academic version has certain limitations in modeling and performing more advanced analyses, but it meets the requirements of this research [11].

According to recommendations and instructions from relevant documentation on fracture mechanics in Abaqus software, a Finite Element Method (FEM) model was created for analysis [11]. The analysis was conducted on a 2D model with dimensions of 1 mm x 1 mm (Figure 12a).



a) Geometry of the model with applied load b) Model divided into a finite number of elements

Figure 12 FEM model in Abaqus CAE

The applied element type in the model is CPS 8 ("8 node biquadratic plane stress quadrilateral element"), while the region around the crack tip is modeled with

CPS 6 ("6 node quadratic plane stress triangle element"). The material assigned to the model is elastic and isotropic, with properties corresponding to concrete: Young's modulus $E = 30 \text{ GPa}$, Poisson's ratio $\nu = 0.2$, and density $\gamma = 2.4 \text{ t/m}^3$.

Due to the limitations in Abaqus software regarding unit selection for specific input quantities, all dimensions were standardized to the same unit. In our case, all units were expressed in millimeters.

The entire model is meshed into a finite number of elements (Figure 12-b). Each finite element is of the same type as the overall model. The mesh density applied is $0.09 \text{ mm} \times 0.09 \text{ mm}$.

Considering the computational constraints, it is nearly impossible to account for all factors influencing crack propagation. Therefore, the loading applied to this model is simplified to pressure along the upper edge of the model, acting in the direction of the Y-axis.

For the analysis of both blasting and non-blasting factors, the same model was used, but with different analysis parameters applied in each case.

Regarding the constraints, they are the same for all cases. The entire model is restricted in movement along the X and Z axes, while movement along the Y axis is allowed. The model is constrained along its lower edge in all axes using the "ENCASTRE" option ($U1=U2=U3=UR1=UR2=UR3=0$), while loads are applied along the upper edge of the model.

To determine the amount of pressure required for the appropriate crack response, a separate analysis was conducted. Based on the results of this analysis, it was determined that for a crack response to blasting factors, in the form of a $12 \mu\text{m}$ expansion, a pressure of $\sigma = 260 \text{ MPa}$ needs to be applied, and for a $42 \mu\text{m}$ expansion, a pressure of $\sigma = 900 \text{ MPa}$ is required.

Regarding the crack's response to non-blasting factors, a pressure of $\sigma = 4440 \text{ MPa}$ is needed for a crack expansion of $210 \mu\text{m}$, for a $48 \mu\text{m}$ expansion, a pressure of $\sigma = 1015 \text{ MPa}$ is required, and for a $10 \mu\text{m}$ expansion, a pressure of $\sigma = 220 \text{ MPa}$ is necessary. The load value for each analysis gradually increases with the number of increments, from 0 to the maximum load value.

The duration of the crack response analysis to blasting factors, for both cases, is 0.033 seconds. The total analysis time is divided into 100 increments, with the duration of each increment being 0.00033 seconds.

The duration of the crack response analysis to non-blasting factors is, for the shaded side, 129600 seconds or 36 hours, for the partially sunny side, 57600 seconds

or 16 hours, and for the sunny side, 50400 seconds or 14 hours. The total analysis time is divided into 1000 increments, with the duration of each increment being 129.6 seconds for the shaded side, 57.6 seconds for the partially sunny side, and 50.4 seconds for the sunny side.

The analysis focused on two parameters: the Stress Intensity Factor (SIF) at the crack tip (KI) and the strain energy in the entire model (Figure 13).

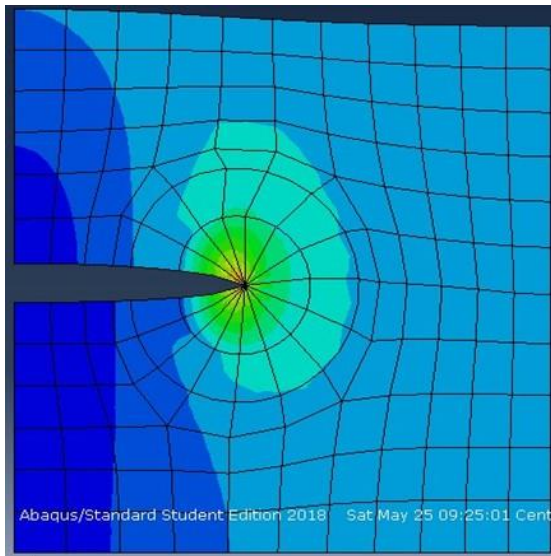


Figure 13 Model of the crack after FEM analysis

The obtained results are presented in the form of graphs "SIF-Time" and "Energy-Time," which can be seen in the following figures (Figure 14 and Figure 15).

From the monitoring results of non-blasting factors, it can be seen that the largest comparator displacement was on the sunny side. Hence, these results were taken into comparison with the blasting factors for further analysis.

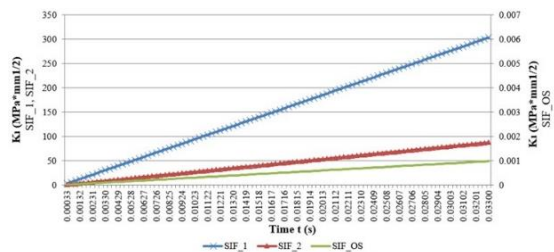


Figure 14 SIF versus Time, all influences

It can be seen from Figure 14, that stress intensity

factor (SIF) linearly increases over time, thus representing a linear function of the form $y = kx$. If in the expression $y = kx$ changes are made in a way that $y = \text{SIF}$, $x = \text{Time} \Rightarrow \text{SIF} = k \cdot \text{Time}$, then $k = \frac{\text{SIF}}{\text{Time}}$. Following this fact, we can calculate the coefficient k for each function.

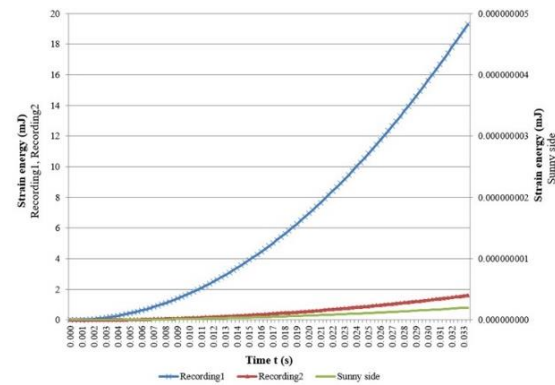


Figure 15 Strain Energy versus Time, all influences

Blasting factors:

- Recording 1: $k_1 = \frac{\text{SIF}_1}{\text{Time}_1} \Rightarrow k_1 = 9\,181.91$ (2)

- Recording 2: $k_2 = \frac{\text{SIF}_2}{\text{Time}_2} \Rightarrow k_2 = 2\,652.55$ (3)

Non-blasting factors:

- Sunny side: $k_{OS} = \frac{\text{SIF}_{OS}}{\text{Time}_{OS}} \Rightarrow k_{OS} = 0.029659$ (4)

If we compare the slope coefficients k_1 , k_2 , and k_{OS} , we can see that $(k_1, k_2) \gg k_{OS}$. It can be said that due to blasting influences (Recordings 1 and 2), the stress intensity factor (SIF) at the crack tip increases much faster over time compared to non-blasting influences (Figure 14). Assuming that the stress intensity factor (SIF) at the crack tip is equal for both blasting and non-blasting factors, we can calculate how many times faster the SIF increases during blasting influences at the crack tip.

$$\text{SIF}_1 = \text{SIF}_{OS} \tag{5}$$

$$k_1 t_1 = k_{OS} t_{OS} \tag{6}$$

$$t_{OS} = \frac{k_1 t_1}{k_{OS}} \tag{7}$$

$$t_{OS} = 309\,582.59 t_1$$

SIF_1 – Stress intensity factor 1(blasting influence),
 SIF_{OS} - Stress intensity factor for the sunny side (non-blasting influence),

k_1 – directional coefficient for Recording 1,

k_{OS} - directional coefficient for sunny side,

t_1 – time for Recording 1,

t_{OS} – time for sunny side record.

In addition to the stress intensity factor at the crack tip, the strain energy in the entire model was also monitored. In Figure 15, we can observe the increase in strain energy over time for all influences. Strain energy follows a quadratic function of the form $y = kx^2$. Using a similar analogy as with SIF, we can express this as $y = \text{Energy}$, $x = \text{Time} \Rightarrow \text{Energy} = k \text{Time}^2$, and further calculate the coefficient k .

Blasting factors:

- Recording 1: $k_1 = 17\,728.65$

- Recording 2: $k_2 = 1\,479.58$

Non-blasting factors:

- Sunny side: $k_{OS} = 1.849796863 \times 10^{-7}$

It can be observed that $(k_1, k_2) \gg k_{OS}$.

It can be said that due to blasting influences (Recordings 1 and 2), the stress energy per unit time increases much faster compared to non-blasting influences.

4. Conclusion

By performing an FEM analysis of the obtained reactions in ABAQUS, it was shown that although the crack response is larger under non-blasting factors, the strain energy and stress intensity factor per unit time are much larger under blast influences. The strain energy is 9.58×10^{10} times larger, and the stress intensity factor at the crack tip is 309583 times higher due to the dynamic loading, observed over a period of 0.033 seconds.

The study of the obtained results shows that dynamic loading caused by the blasting activities prevents adequate and timely stress distribution in the structural elements of the object. As a result, there is a risk of material fatigue, further damage, or the appearance of new defects in the structure.

Based on the above, future research could focus on determining the critical values of the stress intensity factor, i.e. the point at which material fracture and crack progression could occur. In addition, the effects of blasting and non-blasting factors on the overall damage to the structure could be investigated. Among other aspects, the condition of the building, the type of soil on which the building's foundation stands, the building's location, the construction method, the duration of exposure to vibrations, the number of basions, etc. should also be considered.

It is evident that even in cases where the impact of blasting is significantly less than other factors, it should not be neglected, and its impact on nearby structures should always be monitored.

Acknowledgements

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ANALIZA REAKCIJA PUKOTINA NA OBJEKTIMA USLED MINERSKIH I NEMINERSKIH FAKTORA

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Izvod

Seizmički talasi izazvani minerskim aktivnostima mogu biti izvor oštećenja na objektima. Najčešće oštećenje je pojava novih pukotina ili proširenje postojećih. Objekti su takođe podložni uticajima faktora životne sredine. U zavisnosti od uslova, temperatura i vlažnost mogu izazvati jaču reakciju u pukotinama nego miniranje. Međutim, efekti ne-minerskih faktora traju znatno duže od efekata miniranja, pa se opterećenje postepeno povećava, omogućavajući ravnomernu i pravovremenu raspodelu napona oko vrha pukotine. S druge strane, minerski faktori deluju tokom kratkog vremenskog perioda, što za rezultat ima brz porast faktora intenziteta napona na vrhu pukotine i brže oslobađanje energije. Analiza ovih uticaja primenom FEM metode izvedena je na modelu u softveru ABAQUS CAE. Rezultati analize pokazuju da je uticaj minerskih faktora značajno veći u poređenju sa uticajem ne-minerskih (ekoloških) faktora. Energija deformacije i faktor intenziteta napona po jedinici vremena su znatno viši pod uticajem minerskih faktora. Energija deformacije je $9,58 \times 10^{10}$ puta veća, a faktor intenziteta napona na vrhu pukotine je 309583 puta veći usled dinamičkog opterećenja, posmatrano tokom perioda od 0,033 sekunde.

Ključne reči: seizmički talasi, miniranje, FEM metoda, ABAQUS CAE, pukotina, faktori životne sredine.

A STUDY ON MULTI-PROJECT MANAGEMENT IN THE MINING AND GEOLOGY SECTOR IN SERBIA: A CASE ANALYSIS

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Abstract

This paper describes the basic concept of multi-project management in the science and research organizations in Serbia and worldwide. A brief discussion was held on the sources of funding for these projects, and several proposed solutions to problems that may arise in the management of projects in the field of mining, were considered from the perspective of worldwide practice. An overview of completed projects in the field of mining and geology in the period from 2010 to 2023 is given using the example of a case study of a selected scientific and research organization, the Bor Mining and Metallurgy Institute, by type and number of projects and sources of funding. A brief analysis of the success of multi-project management in this institution was carried out. Considering the years of project development, it was determined it was found that the greatest success of multi-project management has been achieved in the last five years, which indicates the good business strategy of the Institute. The financing structure has shown that the largest number of projects in this institution, in the given period was financed by the private sector, i.e. the Chinese mining company Serbia Zijin Copper Bor (formerly RTB Bor).

Key words: multi-project management, financing, project, portfolio, case study.

1. Introduction

1.1. General concept of the multi-project management in the scientific and research organizations

The concept of multi-project management is found in the organizations dealing with different fields of activity and having in common that their portfolio consists of not just one, but several projects that form the basis of their business. The scientific and research organizations are typical representatives of such organizations. Their business activities are carried out precisely through the development and implementation of numerous projects of various types, depending on the field for which they are registered. For the effective management of numerous and diverse projects, it is not enough for a scientific and research organization to have the staff, organization and other prerequisites for the successful management of individual projects, the prerequisites for implementation of the multi-project management must also be in place [1].

The concept of multi-project management is an important factor in integrating the key functions of any organization, especially a science and research organization [2]. According to Levine, 2005 [3] multi-project management is a comprehensive system, i.e. the management principle of a large number of projects (portfolio) as an integrated whole of all projects of a scientific and research institution, and all with the aim of realizing its tasks and vision [3]. At the same time, the project management, i.e. management of individual projects, is one of the essential components of the multi-project management model [4]. In this context, the established and effective project management process is an essential prerequisite for introduction and implementation the multi-project management process in the organization.

When projects are selected for implementation in the organization (as a phase of multi-project management), they move from the competence of multi-project management to the competence of project management (see Figure 1) [5]. These facts point out

how the management of individual projects and multi-project management are the related and mutually dependent processes [6]. The specific culture and values of the employees are also very important in an organization that introduces and implements the multi-project management. Some of the specific cultural values of a multi-project organization, in the context of adopting the concept of multi-project management, are the following:

- Projects are seen as strategically important elements that, on the one hand, enable the implementation of business strategy, and on the

other, influence the business strategy;

- Autonomy and self-organization of the projects is enabled by the top management;
- Leadership implies the ability to recognize the vision and strategy of the organization, but also to connect them with the organization projects;
- Continuous development and survival of the organization should be based on the projects;
- Project management is not considered as a competence and qualification of the specific professionals, but is most closely related to the general management and all its owners [7, 8, 9].

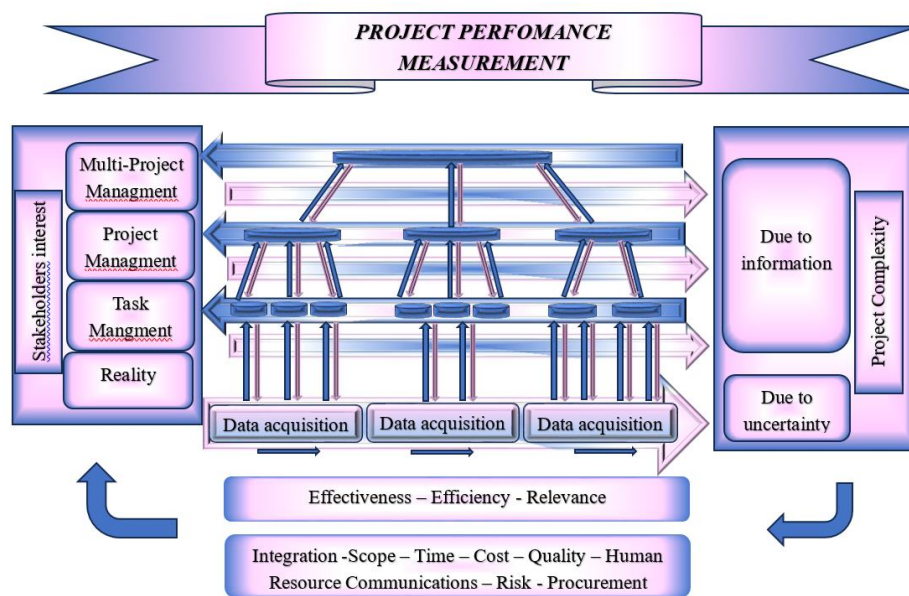


Figure 1 Project implementation measurement hierarchy

Based on a well-developed model, the multi-project management process is introduced and implemented in ten steps in accordance with the generally accepted world PMI (Project Management Institute) standards for project portfolio management: (1) categorization; (2) identification of opportunities and needs; (3) evaluation of options; (4) selection; (5) prioritization; (6) portfolio optimization and adjustment; (7) authorization; (8) implementation and planning of projects; (9) portfolio status reporting; (10) portfolio improvement [10].

1.2. Project financing in the scientific research organizations

The portfolio of the scientific and research organization projects is mainly dominated by the so-

called R&D (*Research and Development*) projects, i.e. the scientific and research development projects that include a wide range of activities with the aim of knowledge improvement, development the new technologies and improvement the existing products or processes [11]. These projects are very demanding in terms of the scope and investment period. These are expensive and long-term projects that require the stable and long-term financing in terms of providing the funds needed to implement the project. The sources of funding for the science and research projects can be internal or external, depending on which science and research organizations carrying them out. The internal funding sources are the resources of organization itself and include the use of profits, reserves, sale of assets or reinvestment of income into projects. External funding is

a type of funding where funds are requested from sources outside the organization. The external funding sources in the broadest sense can be: the profit organizations, the government, the private non-profit sector, international funds and others [12].

In addition to the R&D projects, many scientific and research organizations are engaged in the development of projects for commercial purposes, mainly funded by the profit-making companies.

2. Multi-project management in mining

Nicholas and Steyn [13] stated that the goal of any

project is to hit a three-dimensional target: complete the work for a customer or end-user in accordance with the budget, schedule, and performance requirements. They proposed the concept of project goal as a target point in the three-dimensional space (see Figure 2), where the budget represents the total project costs, schedule is the time period specified for finishing all demanding tasks, and performance requirements are related to the "project end-item, deliverables, or final result, including necessary attributes of the final product or service, technological specifications, quality and quantity measures, and whatever else is important to the customer or end-user [13].

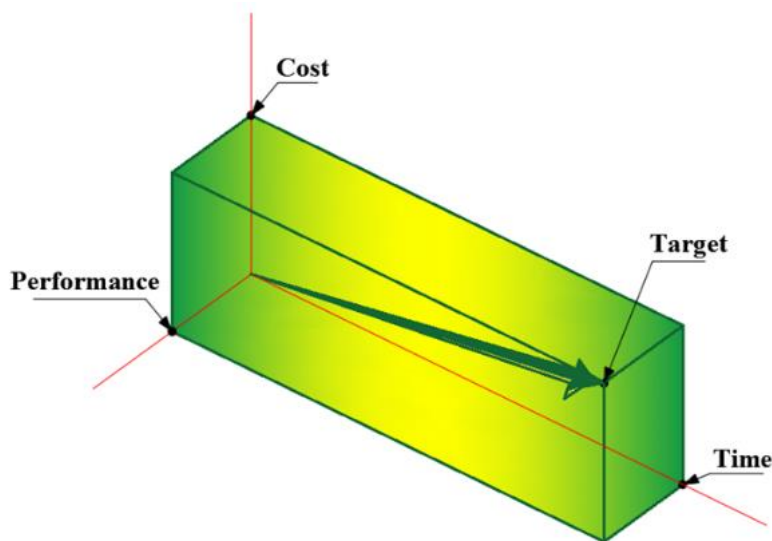


Figure 2 Project target represented through three dimensions

In order to achieve this goal, especially when it comes to the management of multiple projects, it is necessary to see all the influential factors that may be important for the success of each project implementation. According to Riesener et al., 2023 [14] the critical success factors in the multi-project management are: (1) competence and skills management; (2) identification of bottleneck resources; (3) limitation of ongoing projects; (4) consideration of economic aspects due to project delays; (5) use of cycles or cadence; (6) flexibility; (7) decision support by the digital tools (& AI); (8) realistic project planning and (9) global controlling of the multi-project environment. It is also believed that the risk management belongs to this list [14].

Knowledge of critical factors is of great importance

for multi-project management in general, and especially in the mining sector, where a large number of scientific disciplines are interwoven within the framework of various types of mining projects, ranging from the scientific and exploratory ones to the projects, developed for the economic issues, such as: Geology, geomechanics, exploitation, mineral processing and processing technology, construction, mechanical engineering, electrical engineering, automation, environmental protection, occupational safety, economic analysis, etc. For example, the design and construction of a mine, processing plant and infrastructure represent a very complex and risky business endeavor, with a large number of steps that need to be taken during the various phases of research and design (see Figure 3) [15].

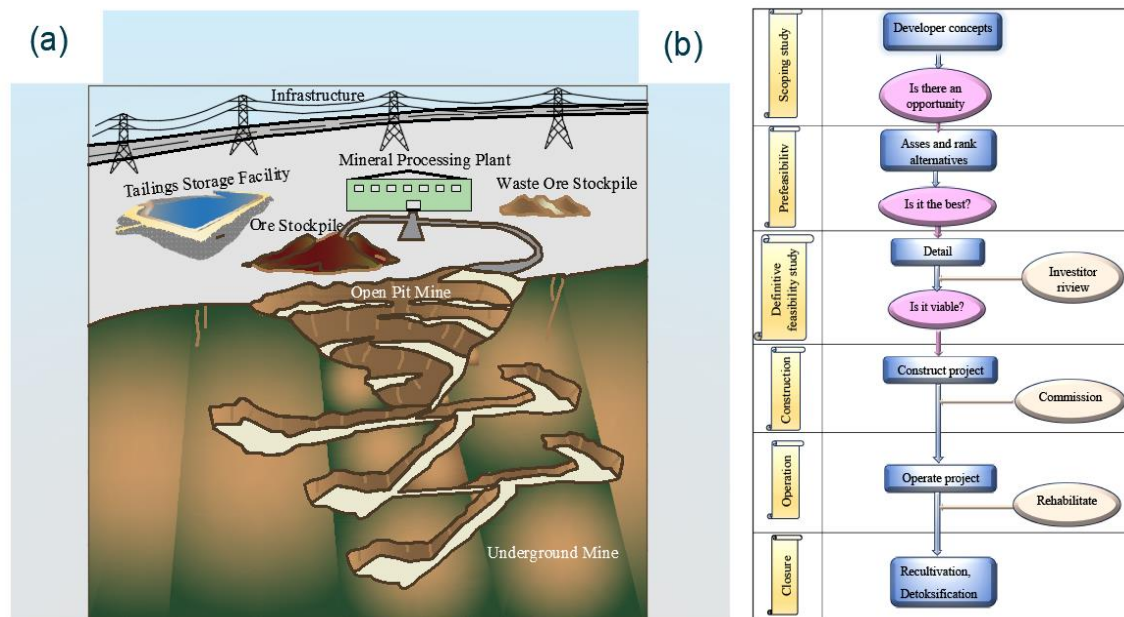


Figure 3 Schematic view of a mine design:
(a) Representative mining project facilities (b) Mining project development framework

2.1. Challenges and solutions

By considering, identifying and optimizing the effect of critical factors in all of the above phases, given in Figure 3 (where each of these project phases serves an important purpose and requires a specific set of management skills [16]), it is possible to achieve the successful multi-project management in the area of mining [17]. Various researchers give suggestions on how to improve the project company performances as effectively as possible and to overcome some of the problems arising during development of this project type.

High competency and skill management enable the good project performances [14]. Litvinenko et al. 2022 [18] stated that the level of professional competence, education and technical, managerial and leadership skills of the mining company engineers represent the equivalent of a trust in such activities of the company, its development and ability to meet the environmental, social and governance principles and sustainable development goals [18]. Kowszyk et al., 2023 [19] described how the management conflict in the mines from four Latin American countries (Chile, Mexico, Brazil and Peru) can have a negative impact on the social, environmental and economic circumstances [19].

According to Riesener et al., 2023 [14], the identification of bottleneck resources in the multi-project environment is not easy due to a high complexity, but usually the employees with special skills represent the bottleneck resources [14]. For this reason, a mining company approach to human resource management policy is very important. Rubbers, 2020 [20] gave an example of the human resource management policy of the new mining projects in the Congolese Copperbelt [20]. Recognizing the resource bottlenecks and seeking the optimal resource allocation scheme is crucial to achieve the overall optimization of the project schedule and resource arrangement [21].

In the multi-project management, it is very important to keep the number of ongoing projects under control (not to run too many projects at once), and the probability of timely project completion can be usually increased by setting an appropriate project buffer [14, 22, 23]. Therefore, the project company must also predict the solution of the multi-project scheduling problem and consider the economic aspect (potential reduction of profit), if penalties are to be paid due to the project delays [14, 24]. As an important step in the multi-project management strategy, Riesener et al., 2023 [14] recommend working in fixed cycles (cadences) that “create a flow and improve the planning accuracy”.

The use of various digital tools (including artificial intelligence methods) to aid management decision making, is highly desirable considering the mining institutions involved in planning [25, 26]. There is a whole range of the project management software on the market that can be used for this purpose [27]. Also, a potential of artificial intelligence to contribute to the effectiveness of the project management is not negligible [14]. For example, Ben Kraiem et al., [28] proposed the machine learning algorithms to select the appropriate project management methodology. Zhang et al., 2020 [29], described a deep neural network-based ant colony optimization algorithm for estimation the capital costs of the mining projects which can be used in development of the mining projects.

Simultaneous multiple-project management in the research institutions can be very difficult, short-period and high-risked. It is very important to select the appropriate projects and also to rank them according to the mission, orientation and plan of strategic development [21]. Flexibility and realistic project planning play an important role in this strategy [14].

Mastering the multi-project environment and risk management are crucial for any project success. According to Santos et al., 2023 [30], the project control involves monitoring the progress and performance of the project, controlling the expected results and taking the necessary corrective actions if there is a deviation from the original plan [30]. On the other hand, the mining projects are exposed to a high risk due to the complexity, size, uncertainty and high cost [31, 32]. Importance of the risk management in the mining projects is described through several practical examples. For example, Chinbat, 2011 [31] provides an extensive analysis of the risk management process in the mining projects, based on practical experience from Mongolia, until Badri et al., 2013 [33] proposes a risk management methodology in the underground mining projects in Quebec, Canada. Jiskani et al., 2022 [34] and Kamel et al., 2023 [35] combine a risk analysis for mining projects with artificial intelligence. Other also describe the problem of risk and uncertainty in the mining projects in different countries - Germany [36], Turkey [37] and Gabon [38].

2.2. Multi-project management and financing of the projects in the scientific and research organizations in Serbia

Considering the multi-project management, the

scientific and research organizations, as well as the business companies in Serbia have undergone many trials and challenges over the past decades. The fact is that the transition period in Serbia towards Europe and the world is still ongoing, so the challenges facing the scientific and research organizations, dealing with the multi-project management, are specific. Factors affecting the multi-project management in the science and research organizations in Serbia are:

1. Limited resources - Science and research organizations in Serbia often face limited financial resources for research, including funds, equipment and employees, which can be challenging and stressful.
2. Administration and regulations - Science organizations in Serbia often have to navigate complex bureaucratic processes in order to obtain funding and other resources for their research projects. This can slow down the decision-making and project deadlines.
3. Brain drain - Serbia is facing a significant brain drain. Many highly qualified researchers are leaving the country to find better opportunities abroad. This can lead to a shortage of experienced researchers, making it difficult to effectively manage the numerous research or economic projects.
4. Lack of collaboration and communication - Collaborative research is crucial for scientific progress, but scientific organizations in Serbia often struggle with cooperation due to the limited resources and competition for funding. This can make managing multiple projects that require collaboration between different teams and departments a challenge [39, 1].

The aforementioned statements generally apply to all sectors, including mining. To overcome these challenges, the scientific organizations in Serbia need to implement effective project management practices that prioritize resource allocation, communication, and collaboration. The effective project management tools, including project management software, can help organizations to manage the multiple projects more efficiently and meet their research goals. In addition, more intensive cooperation and partnership with the other organizations in Serbia and abroad can help to the scientific organizations in Serbia to gain access to the resources and expertise for the effective multi-project management [40].

The project funding models are used in the scientific and research institutes in the field of mining to provide

the funding for research projects related to mining. These projects may include the research, development and optimization of mining processes and technologies, as well as the environmental and social impact assessments.

Some of the project funding models that can be used in mining science and research organizations are:

1. Grants from government agencies, non-profit organizations and private foundations to support their research projects;
2. Corporate funding - mining companies can provide funding to academic and research organizations to conduct the research related to mining processes and technologies;
3. Joint ventures - the scientific and research organizations can partner with the mining companies or other organizations to carry out the mining-related research projects;
4. Public-private partnerships - where public sector entities can provide funding and regulatory support, while private sector entities can provide technical expertise;
5. Corporate partnerships - where mining companies can partner with the scientific and research organizations in order to fund the research projects that align with their business objectives;
6. Donations from individuals or organizations can provide funding for scientific research;
7. Consortia - this approach involves the formation of consortia for joint funding and project management [40].

It is important for research organizations to carefully evaluate the advantages and disadvantages of each funding model and choose the one that best suits their needs.

3. A case analysis

The Mining and Metallurgy Institute Bor (abbreviated to MMI Bor) is presented as an example of a scientific and research organization in Serbia that successfully manages multiple projects in the field of mining.

The Mining and Metallurgy Institute Bor is a scientific and research institution, owned by the Republic of Serbia in the fields of research, design, production and processing of mineral raw materials. Today, the MMI is a leader in the country and one of the most important institutions in Southeast Europe with its human and technical capacities and financial stability. It also represents one of the most important supporters of

scientific and research development in the field of mining.

The MMI Bor, as a part of its scientific and research activities, develops the scientific and research projects in the fields of geology and mining and conducts research in the field of exploitation of deposits and preparation of metallic and non-metallic mineral raw materials [41].

In addition to scientific and research work the Institute realizes the preparation of expertise and studies, pre-investment and investment studies and projects, investment programs, investment-technical documentation, project studies and other investment documentation for the implementation of investment works in the country and abroad, in the field of geology and mining, which are of interest to the Republic, the region and local self-government, as well as within the scope of work in the field of environmental protection and ecology (recycling of waste and other materials) [41].

The period from 2010 to 2023 was selected to analyze the success of the multi-project management in the MMI Bor. The number of completed projects was defined by the type and year of development (or the start of implementation, in the case of the scientific and research projects), taking into account all the realized projects in the field of mining and geology. The study includes projects prepared in the form of investment and technical documentation in accordance with the Law on Mining and Geological Explorations ("Official Gazette of RS", No. 101/2015, 95/2018 - other laws and 40/2021), then technological research in the field of mineral processing, environmental impact studies related to mining facilities, as well as scientific and research projects from the national and international cooperation programs. Figure 4 shows the type and number of projects by year of development/implementation. Figure 5 shows the percentage share of projects by year of development/implementation. The presented data were obtained from the MMI archive.

For the purpose of clarification, Table 1 describes each type of project documentation in more detail.

Over the last 14 years, the Institute has been involved in the development a total of 146 different types of projects in the field of mining and geology. Based on the data from Figures 4 and 5, it can be clearly seen that the progress has been made in the field of multi-project management in the MMI Bor over the last 5 years. In the observed period from 2010 to 2023, 50% of the projects were developed in the last 5 years, compared to the

previous nine-year period 2010-2018, in which 50% of the projects were also placed in the mining and geology field. This means that the MMI has almost doubled the production of project documentation in the last 5 years, which speaks for a good organization and adequately implemented rules of the multi-project management. It should be added that the MMI employs highly skilled staff in the fields of mining, geology, mechanical engineering, electrical engineering, construction and economics with a modern software support for development all types of projects.

Besides the employees, software tools are also available for modelling and designing in fields of geology, underground and open pit mining, mineral processing, pyrometallurgy, electrometallurgy, refining, mechanical and electrical engineering, automation engineering, civil engineering, development and

application of hardware and software, industrial informatics, etc. Some of the licenced software programs in the field of mining and geology that MMI has at its disposal are GEMCOM v 6.1.4.; MINEX v 5.2.1.; MINESCHED; SLOPE/W)

Some of the efficiency factors that have contributed to the increase in the number of successfully placed projects in the last 5 years of the Institute's work are:

- introduction of even more modern software tools that enable more efficient and faster problem solving,
- employment of qualified personnel,
- good work organization and well-thought-out prioritization of projects on the time scale,
- good employee motivation and improvement of working conditions (working environment and financial moment).

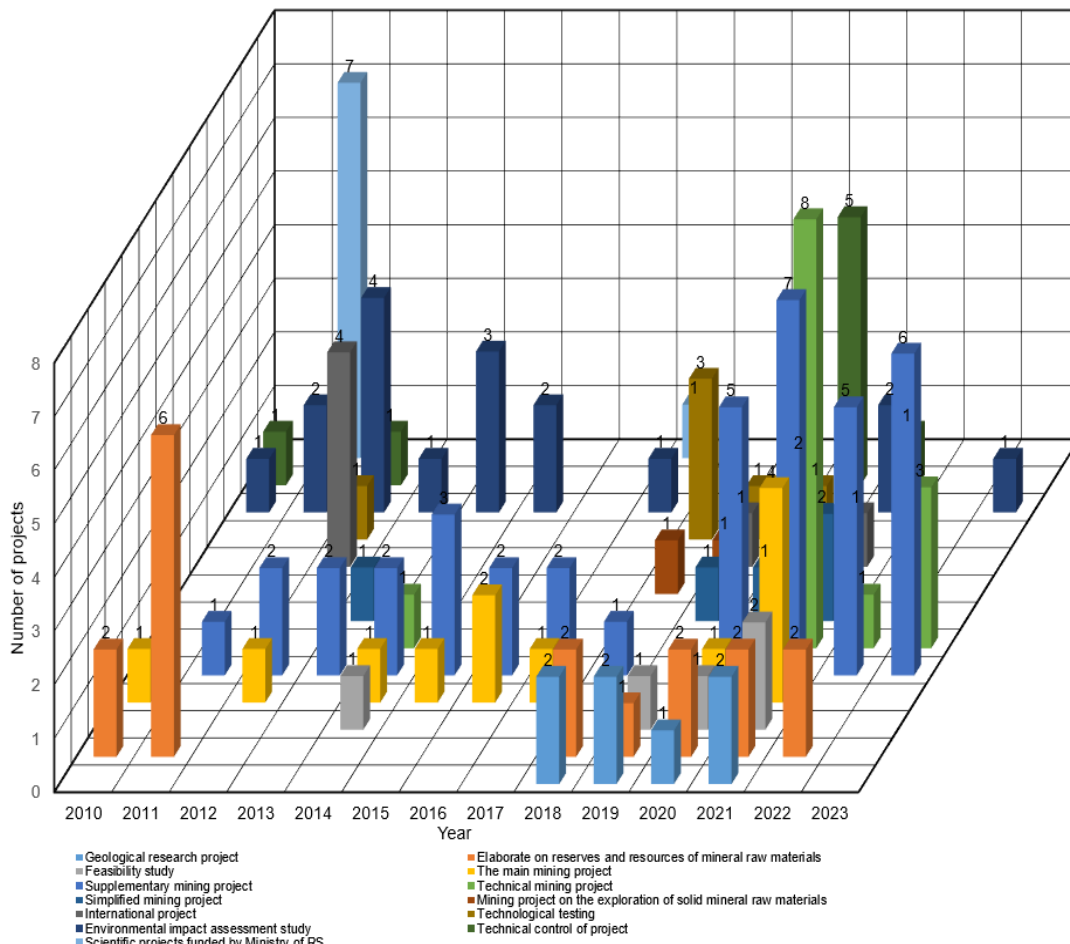


Figure 4 Type and number of projects developed/implemented in the MMI Bor in the period from 2010 to 2023

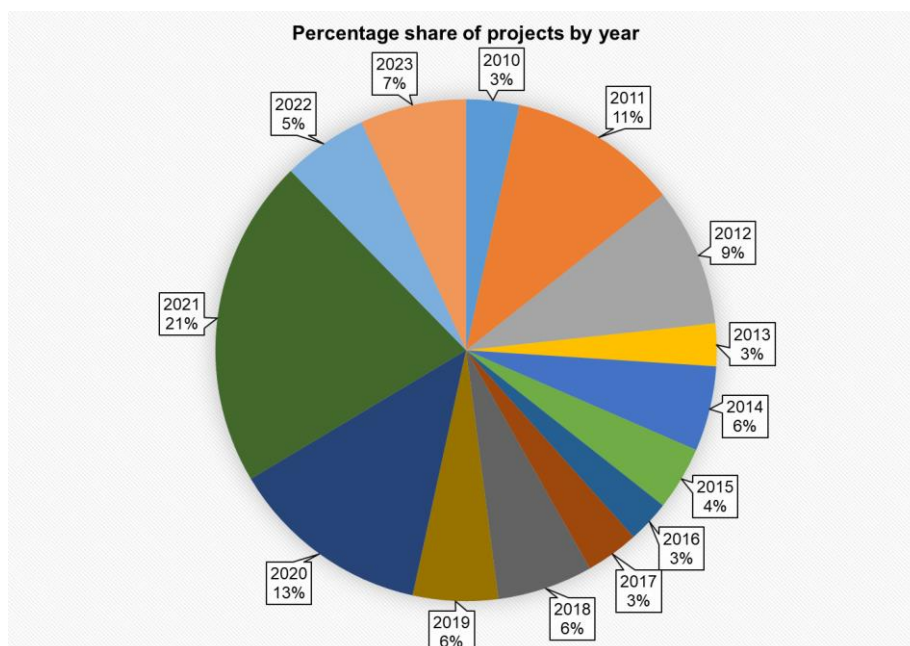


Figure 5 Percentage share of projects by year in MMI Bor

Table 1 Description of project documentation

Geological research project	Describes geological and mineralogical characteristics of the research area, classification and categorization of mineral reserves.
Elaborate on reserves and resources of mineral raw materials	Document on the results of geological research of a specific deposit of mineral raw materials, the quantities and quality of researched raw materials or resources, their classification, technical possibilities and exploitation conditions, as well as the expected economic effects.
Feasibility study	Describes the conditions and conceptual solution of the method of exploitation and preparation of mineral raw materials.
The main mining project	The project of exploitation, maintenance and construction of new underground and surface mines as well as facilities for the processing of mineral raw materials.
Supplementary mining project	Project that is created for deviations from the main mining project.
Technical mining project	Project that is prepared in accordance with the main and supplementary mining project for the technological operations of mining works.
Simplified mining project	For all minor deviations from the adopted technical solutions processed in the technical project.
Mining project on the exploration of solid mineral raw materials	The project on the basis of which mining works are carried out within the approved project of geological research.
International project	A scientific research project that involves international cooperation.
Technological testing	Laboratory experimental research in the field of mineral processing.
Environmental impact assessment study	Analyzes and evaluates the quality of environmental factors and their sensitivity in a certain area.
Technical control of project	Includes control of the project in terms of compliance with the law and other regulations in the field of mining.
Scientific projects funded by Ministry of RS	Project from the scientific research programs funded by the Ministry of RS.

The educational structure of MMI Bor is very specific in the context of motivation for organizational change and project development. It is an employee structure that requires a particularly sophisticated and balanced approach when it comes to motivation for ongoing work activities and projects as well as for planned organizational changes. That is why such an organization creates and nurtures special organizational communication, culture and special human resources management, as special aspects of motivating employees to work and change [42].

The management at MMI Bor is quite stimulating in terms of motivating employees to work and change. The activities that receive the most attention, in order to maintain and increase employee motivation, are employee development and rewarding. Regarding remuneration in MMI Bor, material rewards in the form

of salaries presuppose opportunities for the development of employees and their advancement in scientific, research and professional titles. This means that the management of this organization, both materially but largely by intangible rewards, motivates its employees [42].

The projects in the MMI Bor are financed by the profitable third parties from the country and abroad (considering the preparation of investment and technical documentation), then by the Ministries of the Republic of Serbia (national scientific and research projects), as well as by the European Union (international scientific and research projects). Figure 6 shows the type and number of projects by the type of financing. Figure 7 shows the percentage share of projects by the type of financing. Data on the amount of finance were not available.

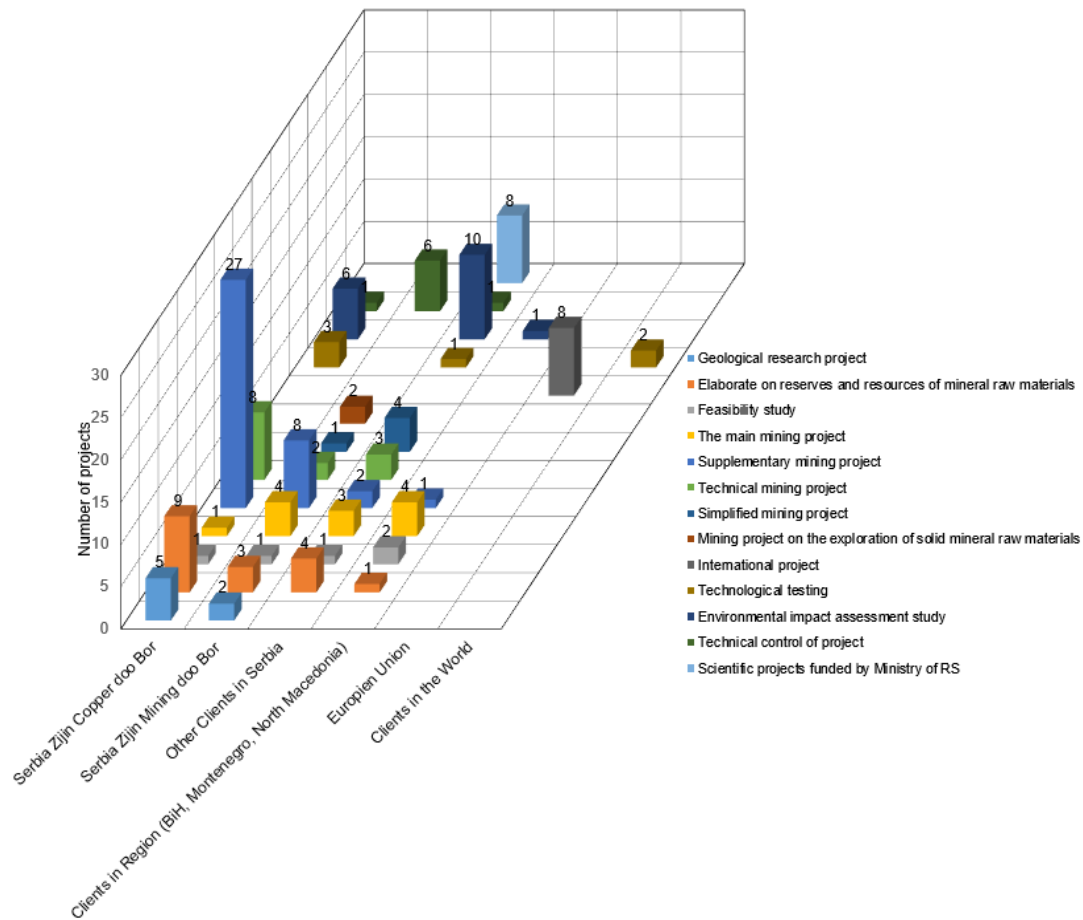


Figure 6 Type and number of projects developed/implemented in the MMI according to the type of financing in the period from 2010 to 2023

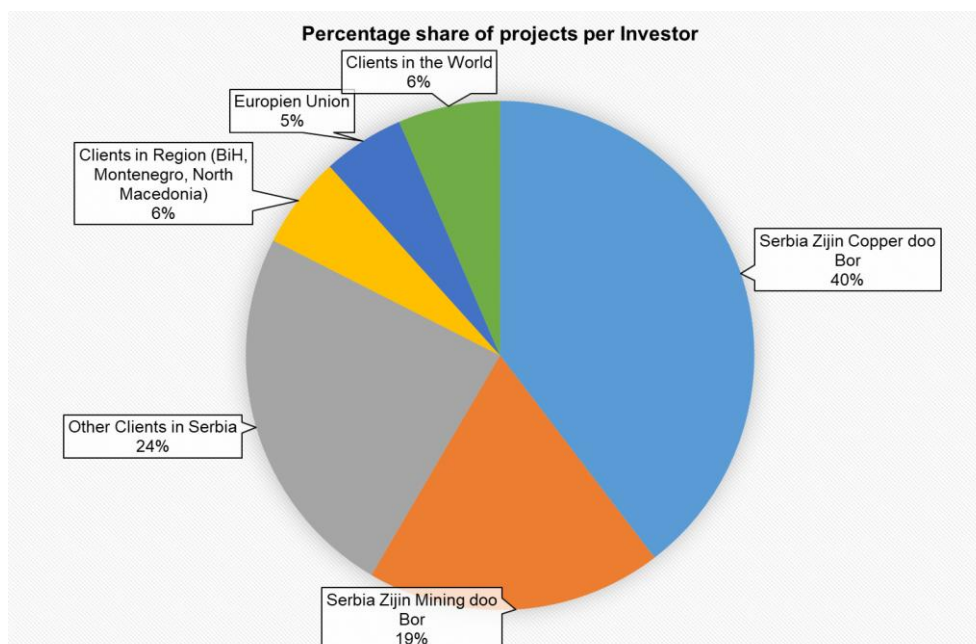


Figure 7 Percentage share of projects in the MMI Bor by type of financing in the period from 2010 to 2023

Figures 6 and 7 show that the largest number of projects, implemented in the period from 2010 to 2023 in MMI Bor, was financed by the third parties, namely the company Zijin Copper doo Bor (former Mining and Smelting Basin Bor) and Zijin Mining doo Bor. This is expected when taking into account the strategic policy of the company Zijin, which is aimed to increase the capacity of all mines in the Bor region. In addition, a significant percentage is occupied by the investors from the Republic of Serbia (24%). Regarding the other types of investments, the business policy of the MMI is aimed at increasing the number of scientific and research projects, financed by the Republic of Serbia and European Union, as well as the number of projects developed for the clients from the countries of the region, Europe and world.

4. Conclusion

The basic concept of the multi-project management is given within the framework of presented research, as well as an overview of influential factors on the multi-project management in the scientific and research organizations dealing with mining.

The Mining and Metallurgy Institute Bor is presented as an example of a domestic scientific and research institution that successfully deals with the multi-project

management. Based on conducted research, the following conclusions can be drawn:

- The concept of multi-project management is found in the organizations that have in common a large number of projects in their portfolio on which their business is based.
- On the basis of a well-developed model, the introduction and implementation of the multi-project management process is carried out according to the defined steps in accordance with the generally accepted PMI world standards.
- In order to implement the successful multi-project management, it is necessary to consider, identify and optimize the impact of a whole range of critical factors in all phases of the project development.
- By integrating scientific research into the management of multiple projects, organizations from the mining sector can improve decision-making processes, reduce risks, improve project performance and promote sustainability.
- The Mining and Metallurgy Institute Bor is a leading institution in Serbia engaged in scientific and research and design in the field of geology, exploitation and processing of mineral raw materials. The project activity of the Institute is presented for the period from 2010 to 2023.

- In the future, the presented MMI model can help both project managers and financiers, to make funding decisions based on resource allocation info, develop risk mitigation strategies and introduce better safety measures and environmental monitoring systems.

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STUDIJA O VIŠESTRUKOM UPRAVLJANJU PROJEKTIMA U SEKTORU RUDARSTVA I GEOLOGIJE U SRBIJI: ANALIZA SLUČAJA

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Izvod

Ovaj rad opisuje osnovni koncept višestrukog upravljanja projektima u naučnim i istraživačkim organizacijama u Srbiji i širom sveta. U radu se kratko razmatraju izvori finansiranja ovih projekata, a analizirano je nekoliko predloženih rešenja problema koji se mogu javiti u upravljanju projektima u oblasti rudarstva, iz perspektive svetske prakse. Prikazan je pregled realizovanih projekata u oblasti rudarstva i geologije u periodu od 2010. do 2023. godine na primeru studije slučaja izabrane naučnoistraživačke organizacije, Instituta za rudarstvo i metalurgiju Bor, po vrsti i broju projekata i izvorima finansiranja. Izvršena je kratka analiza uspešnosti višestrukog upravljanja projektima u ovoj instituciji. Uzimajući u obzir godine razvoja projekata, utvrđeno je da je najveći uspeh višestrukog upravljanja projektima postignut u poslednjih pet godina, što ukazuje na dobru poslovnu strategiju Instituta. Struktura finansiranja pokazala je da je najveći broj projekata u ovoj instituciji, u datom periodu, finansiran od strane privatnog sektora, odnosno kineske rudarske kompanije Serbia Zijin Copper Bor (ranije RTB Bor).

Ključne reči: višestruko upravljanje projektima, finansiranje, projekat, portfolio, studija slučaja.

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4. Author, E. (2012) Article title. In: The name of the Conference. City, Country, Proceedings, 26-35.
5. Author, F. (2013) Report title, link of web pages, (accessed date).

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